COMPARATIVE EVALUATION OF MECHANICAL PROPERTIES OF BASE METAL ALLOYS AND COMMERCIALLY PURE TITANIUM WITH EFFECT OF LASER SURFACE TREATMENT - AN IN VITRO STUDY

Dissertation Submitted to

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In partial fulfillment for the Degree of

MASTER OF DENTAL SURGERY

BRANCH I

PROSTHODONTICS AND CROWN & BRIDGE

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CERTIFICATE

This is to certify that the dissertation titled **"COMPARATIVE EVALUATION OF MECHANICAL PROPERTIES OF BASE METAL ALLOYS AND COMMERCIALLY PURE TITANIUM WITH EFFECT OF LASER SURFACE TREATMENT - AN IN VITRO STUDY"** is a bonafide record work done by **Dr. HARISH GOPAL** under our guidance and to our satisfaction during his post graduate study period between 2010 – 2013.

This dissertation is submitted to **THE TAMILNADU Dr. M.G.R. MEDICAL UNIVERSITY**, in partial fulfillment for the Degree of **MASTER OF DENTAL SURGERY – PROSTHODONTICS AND CROWN & BRIDGE, BRANCH I.** It has not been submitted (partial or full) for the award of any other degree or diploma.

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ABSTRACT

Background: Prosthodontic restorations require metals or alloys with good mechanical properties. CP-Ti has good biocompatibility but is weaker mechanically in comparison to Ni-Cr and Co-Cr alloys. An attempt was made in this study to improve the mechanical properties of CP-Ti using laser peening.

Materials and methods: 51 dumbbell shaped cast samples were fabricated with Ni-Cr (n=17), Co-Cr (n=17) and CP-Ti (n=17). 6 cast samples from each group served as Control group while 11 cast samples were subjected to laser peening (Test group). Cross section of 1 Control and test group sample each of Ni-Cr, Co-Cr and CP-Ti were subjected to microscopic examination following which microhardness was evaluated. Tensile testing of 5 control group and 10 test group samples each for Ni-Cr, Co-Cr and CP-Ti were conducted using Tensometer to evaluate mechanical properties.

Results: Upon laser peening surface hardness increased for Ni-Cr, Co-Cr and CP-Ti samples. Ultimate Tensile Strength and Yield Strength of CP-Ti increased whereas these values reduced for Ni-Cr and Co-Cr samples. Modulus of elasticity increased for Co-Cr and CP-Ti while it reduced for Ni-Cr. Percentage of Elongation reduced for CP-Ti samples.

Conclusion: Laser peening for CP-Ti resulted in improvement of mechanical properties.

Keywords: CP-Ti, Mechanical properties, Laser peening, Nd:YAG laser Tensometer.

INTRODUCTION

Dental casting alloys play a prominent role in the fabrication of fixed, removable and implant prostheses. The use of alloys provides physical, mechanical and biologic properties that are required for successful, long-term prosthodontic restorations.[46,53,54,55] The significant improvement in the properties of casting alloys ensures their role as the principal material for years to come since no other material has the combination of strength, modulus of elasticity, wear resistance and biologic compatibility that a material must have for long term survival in the mouth.[55]

The American Dental Association (ADA) divides casting alloys into three groups on the basis of wt % composition as high-noble, noble and base-metal alloys.[13,54,55] The ADA revised the classification system (Mar 2003) for alloys for fixed prosthodontics with regard to the use of titanium and titanium alloys in dentistry. The Council classified casting alloys as high-noble, titanium, noble and base-metal alloys in the revised classification system because of the excellent biocompatibility of titanium.[1]

The cast restorations must be made of an alloy that meets certain minimum requirements for strength, stability, castability, corrosion and tarnish resistance, burnishability, polishability and biocompatibility for the long term success.[44] Metal-ceramic alloys have additional requirements that include higher melting temperature, thermal compatibility with ceramics, oxide formation and sag resistance.[46] Several mechanical properties like ultimate tensile strength, yield strength, flexural strength, torsional strength, fatigue strength, impact strength, modulus of elasticity, percentage elongation, malleability, fracture toughness and hardness are important for good clinical performance of dental alloys.[2,15] Among these properties, the ultimate tensile strength, yield strength, modulus of elasticity and percentage elongation are the most important.[5,15,16,18,31,34,37,41,43,45,46,51,54,55,57,58]

Ultimate tensile strength is the maximum stress that a material can withstand while being stretched or pulled before necking.[2,15] It indicates the ability of a metal structure to endure the applied forces.[15,18] Tensile strength is necessary for the prosthesis to withstand occlusal forces within the oral cavity.[36] Yield strength is the amount of stress required to produce a pre-established amount of permanent strain (i.e., change in length) of the alloy.[2,15]

The modulus of elasticity (elastic modulus) is a measure of the stiffness or rigidity of an alloy.[54] The elastic modulus for prosthodontic alloys needs to be high so that the prosthesis can resist flexure, especially in metal-ceramic restorations where any flexure will cause fracture of the porcelain. It is also important for removable partial dentures so that the major connectors have adequate rigidity to prevent flexure during placement and function and will therefore transmit occlusal forces more efficiently to the remaining teeth or other tissues.[54] Resistance to flexure is also beneficial because clasps can be placed into areas of minimal undercut and still provide adequate retention.[15]

The percentage of elongation is the measure of ductility of the material.[5,15] Ductility is the degree to which a material can be permanently deformed by a tensile force without undergoing fracture or rupture. It is required to improve marginal fit of a restoration by burnishing.[7] The hardness of the alloy must be enough to resist occlusal forces but not wear opposing teeth.[15,55]

The high-noble alloys are generally favourable for manipulation and clinical service because of high ductility, adequate yield strength and ultimate tensile strength, excellent castability, excellent porcelain bonding, favourable esthetics, good biocompatibility, excellent corrosion and tarnish resistance, not technique sensitive, good burnishability and easy to adjust and finish, but none of these alloys have a high elastic modulus value.[54,55] In single units and short-span fixed partial dentures, gold-based alloy systems possess ample elastic modulus to prevent this flexure. However, in long span fixed partial dentures, elastic modulus is not sufficient to prevent clinically problematic levels of flexure.[54] The other disadvantages are high cost, poor sag resistance in case of long span fixed partial dentures, low hardness and high density. [2,15]

Noble alloys with lower content of noble elements and inclusion of Cu, Ag and Ga overcome the drawback of low elastic moduli of high noble alloys, thereby increasing the flexural resistance.[2,15] Also, they have better sag resistance than high-noble alloys.[46,54,55] Whereas, the corrosion resistance of the noble alloys is variable; it depends on the microstructure and the presence of corrosion-prone microstructural phases such as silver and copper.[53,54] Also, it has the drawback of higher costs when compared to base metal alloys.[2,15,46,54,55]

The need for better physical and mechanical properties and affordable costs led to the development of base metal alloys.[2,8,15,54,55] The base-metal alloys like Nickel-chromium (Ni-Cr) and Cobalt-chromium (Co-Cr) share high physical properties, and these alloys have higher modulus of elasticity[6,8,46,47] and superior mechanical properties when compared to high noble and noble alloys. They have low density[8] and excellent sag resistance making them suitable for long span fixed partial dentures.[2,15,46,54,55] They are much lower in cost[6,8,53] and have excellent porcelain bonding.[2]

These alloys also have several disadvantages namely higher corrosion in acidic environments,[22,53] risk of patient allergy,[22,53] and difficult in soldering [2] when compared to high-noble and noble alloys. Furthermore, their liquidus temperatures are the highest among all prosthodontic alloys, making them harder to cast, finish and polish and ensure appropriate marginal fit of restoration.[2,8,14] From the standpoint of porcelain application, these alloys all form heavy, dark oxide layers that are more difficult to esthetically manage than those formed by alloys in the noble and high-noble alloy groups.[55] The compatibility of coefficients of thermal expansion between Co-Cr alloys and porcelains may also be problematic.[45]

The base metal alloys, such as Ni-Cr and Co-Cr have been used for the fabrication of fixed and removable prosthesis, but there are concerns about their biological safety following reports of nickel and cobalt sensitivity.[22,43,53]

In recent years CP-Ti and its alloys have become an alternative to gold and base metal alloys due to their excellent biocompatibility, good corrosion resistance, low density, high mechanical sag resistance and relatively low cost.[4,7,9,11,19,21,22,53,54,55] These alloys can be used for all-metal and metal-ceramic prostheses, as well as for implants and removable partial denture frameworks.[7,9,18,25] According to the American Society for Testing and Materials (ASTM), there are four unalloyed grades of CP-Ti (Grades 1-4), based on the concentration of oxygen and iron.

The mechanical strength of pure titanium increases due to the inclusion of impurities during casting.[10] However, this strength might not be sufficient for multi-unit fixed partial dentures and metal frameworks of removable partial dentures[18,26,30,32,33,34,40,57] and are reported to possess low wear resistance.[23,26] Moreover, titanium has a high melting point (1668° C), and a special casting machine with arc-melting capability and an argon atmosphere is typically used, along with a compatible casting investment, to ensure acceptable castability which makes them expensive and technique sensitive.[12,19,20,24,31,59] This high melting point is accompanied by a relatively low thermal expansion coefficient, necessitating special low-expansion dental porcelains for bonding to titanium.[25,61]

Considering the properties of all the casting alloys, none of them satisfy all the physical, mechanical and biologic requirements for the fabrication of prosthodontic restorations.[2,54,55] Various methods like compositional alterations[54] (increasing carbon) and heat treatment of alloys[12,60] have been reported in literature for high-noble, noble and base metal alloys for enhancing their physical and mechanical properties. Recently, laser peening method has been employed for improving mechanical properties of commercially pure titanium and has given good results.[43,57] Laser peening (laser surface treatment) is an innovative surface enhancement process used to improve fatigue life. This process creates residual compressive stresses deep into the surfaces. These compressive surface stresses inhibit the initiation and propagation of fatigue cracks. When laser surface treatment is applied to cast titanium metal frameworks, it is expected that the titanium framework will have high mechanical strength to withstand mastication stresses.[57]

In the literature, comparative evaluation of the various mechanical properties of Ni-Cr, Co-Cr and CP-Ti has been reported.[6,18,38,39,45,46,49,54,55,57,58] The evaluations have been done on both untreated and surface treated alloy specimens.[12,47,60] However, literature regarding the effect of laser peening on the mechanical properties of Ni-Cr, Co-Cr and CP-Ti alloys is recently emerging and sparse.[43,57]

Considering the significance of this new technology in potentially improving the mechanical properties and its relevance to clinical situations, the present in-vitro study was aimed to comparatively evaluate the mechanical properties of base metal alloys and commercially pure titanium with effect of laser surface treatment. Also added to the aim of the study were the following objectives:

1. To evaluate the hardness of Ni-Cr, Co-Cr and CP-Ti test samples at various depths before and after laser peening.
2. To evaluate the ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of Ni-Cr before laser peening.
3. To evaluate the ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of Co-Cr before laser peening.
4. To evaluate the ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of CP-Ti before laser peening.
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11. To comparatively evaluate the ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of CP-Ti before and after laser peening.
12. To comparatively evaluate the ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of Ni-Cr, Co-Cr and CP-Ti before laser peening.
13. To comparatively evaluate the ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of Ni-Cr, Co-Cr and CP-Ti after laser peening.

REVIEW OF LITERATURE

Civjan S et al (1972)[12] stated that the main problems with the base metal alloys are their excessive hardness and inadequate elongation. They studied the effects of heat treatment on the mechanical properties of two nickel-chromium-based casting alloys and concluded that both alloys showed rapid response to heat treatment. Both alloys had similar mechanical and heat treatment characteristics and in their softened state, they lost up to 50% of their as-cast hardness and had elongations of 25 to 45%.

Baran GR et al (1983)[5] in their article on metallurgy of Ni-Cr alloys for fixed prosthodontics has mentioned that the important mechanical properties necessary for dental casting alloys are hardness, yield strength, tensile strength and percentage elongation.

Preston DJ (1984)[44] in his article on metal-ceramic restoration has stated that alloy selection should consider physical properties, mechanical properties, compatibility with a given porcelain, ease of manipulation and cost. Among the mechanical properties he has considered that the yield strength and modulus of elasticity are the most important.

Asgar K et al (1985)[3] conducted a study on influence of different casting machines on castability of crown and bridge alloys. The alloys included one base metal alloy, two high-fusing noble metal alloys and one type III gold alloy. They concluded that there was a significant difference among casting machines and alloys and that the type of casting machine had a stronger effect on castability.

Hensten-Pettersen A (1992)[22] in his article on side-effects of casting alloys has stated that the incidence of side-effects in prosthodontics was about l:400. About 27% of the reactions were related to base-metal alloys containing cobalt, chromium, and nickel and to noble based palladium alloys. They also inferred from various studies that all dental casting alloys had potential for eliciting adverse reaction in hypersensitive patients except unalloyed titanium which was considered most biocompatible among all other casting alloys.

Berg E et al (1995)[7] conducted a study on the mechanical properties of laser welded cast and wrought titanium base and compared them with those of a brazed Type 4 gold casting alloy. Ultimate tensile strength, 0.2 % yield strength and percentage elongation were recorded for joined and unjoined bars. The strength of the laser welded titanium equalled that of the brazed gold alloy, suggesting that dental restorations made of cast and wrought titanium would satisfy ordinary clinical requirements.

Wang R et al (1996)[52] in their review article on titanium for prosthodontic applications have mentioned that the light weight of titanium and its strength-to-weight ratio, high ductility and low thermal conductivity would permit design modifications in titanium restorations and removable prosthesis, resulting in more functional and comfortable use. The low cost of titanium raw material and its favourable microhardness make them attractive for dental prostheses.

Chai T et al (1998)[10] studied the mechanical properties of laser welded cast CP-Ti under different laser welding conditions to find the optimal parameters in terms of duration and voltage (energy level). They found that the voltage was the only significant factor that influenced the ultimate tensile strength and 0.2% yield strength of the joint, whereas the duration was not a significant factor. They concluded that the laser-welded joint achieved superior mechanical properties.

Wataha JC et al (2000)[53] in their review article on biocompatibility of dental casting alloys stated that the single most relevant property of a casting alloy to its biologic safety is its corrosion. Several elements such as nickel and cobalt have relatively high potential to cause allergy. To minimize biologic risks, dentists should select alloys that have the lowest release of elements by using high-noble or noble alloys with single-phase microstructures. They concluded that selection of an alloy should be made on a case-by-case basis using corrosion and biologic data from dental manufacturers.

Zinelis S et al (2000)[62] conducted a study to evaluate the effect of pressure of helium, argon, krypton, and xenon on the porosity, microstructure, and mechanical properties of commercially pure titanium (Cp-Ti) castings. Groups A, C, E, and G were cast under a pressure of 1 atm, and groups B, D, F, and H were cast under a pressure of 0.5 atm of He, Ar, Kr, and Xe, respectively. The VHN of the as-received cp Ti was significantly greater than all the cast groups tested. Groups cast under He showed the highest VHN, yield strength, and fracture stress. They concluded that the porosity and mechanical properties of cp Ti castings are dependent on the gas type and pressure, whereas the microstructure remains unaffected.

Cecconi TB et al (2002)[9] have stated that titanium is the most biocompatible metal available for dental castings. However, they expressed concern about the castability of titanium used on a daily basis. They conducted a study on radiographic evaluation of titanium partial denture frameworks to ascertain whether these castings were technically acceptable for clinical use. Three hundred Grade II titanium removable partial denture frameworks were cast and were evaluated radiographically and 97% were rated acceptable for clinical use and concluded favourably for use of titanium castings on a daily basis.

Liu J et al (2002)[35] examined the joint strength of titanium laser welding using several levels of laser output energy. They observed that the penetration depth by laser was different among the parent metals because the rate of laser beam absorption, thermal conductivity and melting point are different in each metal. Base metals have a greater rate of laser beam absorption and lower thermal conductivity compared to the noble metals. They found that titanium in particular has a very low thermal conductivity and high rate of laser beam absorption which makes it easy for the laser to penetrate into this metal.

Wataha JC et al (2002)[54] in their article on alloys for prosthodontic restorations have stated that several properties of alloys are critical to the clinical performance of restorations which includes the grain size and structure, mechanical properties such as ultimate tensile strength, yield strength, modulus of elasticity and hardness, porcelain bonding properties such as coefficient of thermal expansion and oxide color and biological properties such as corrosion resistance.

Lin Chai-Wei et al (2004)[34] conducted a study to compare the castability and mechanical properties of CP-Ti, Ti-6Al-7Nb and a newly developed Ti-15Mo-1Bi in regard to their as-cast state. Experimental results indicated that the hardened layer thicknesses of three materials were similar. The bulk hardness of CP-Ti was much lower than the other two alloys which displayed similar hardness. The bending modulus of Ti-15Mo-1Bi was significantly lower than CP-Ti and Ti-6Al-7Nb. Tensile test also indicated that the Ti-15Mo-1Bi and Ti-6Al-7Nb alloys have far higher strengths and lower elongations than CP-Ti.

Wataha JC et al (2004)[55] in their article on casting alloys have stated that the the mechanical properties of the casting alloy must be considered important and customized for a particular clinical situation whereas, cost and color are the least important factors in selecting a material for a successful prosthesis.

Eliopoulos D et al (2005)[18] conducted a study to evaluate the effect of the type of the investment material on the thickness of the contamination zone and on the mechanical properties such as modulus of elasticity, yield strength, elongation, and hardness of CP-Ti castings. From the results of this study they concluded that the extent of the contamination zone as well as the yield strength and percentage elongation of the CP-Ti castings were significantly affected by the type of the investment material.

Rocha SS et al (2006)[47] evaluated the effect of different heat treatments on the Vickers hardness of CP-Ti and Ti-6Al-4V cast alloys. They concluded that heat treatments enhanced the hardness of both CP-Ti and Ti-6Al-4V alloy which may be due to the martensitic transformation and micro-structural alteration.

Watanabe I et al (2006)[56] conducted a study to investigate the effect of surface preparation on the Nd:YAG laser penetration into cast titanium and gold alloy. They found that increasing the voltage or pulse duration and decreasing the spot diameter generally increases the laser penetration into the alloys. Other factors affected the laser penetration are thermal conductivity (Tc) and the rate of laser beam absorption (Ba) of the alloys. Lower the Tc and the greater Ba of the alloy, the deeper the laser can penetrate into the alloys.

Oliveira PC et al (2007)[41] conducted a study on the influence of the final temperature of investment heating on the tensile strength and Vickers hardness of CP-Ti and Ti-6Al-4V alloy. From the results they concluded that significant differences in tensile strength and hardness was found only between the materials used and not between the temperatures of the investment mold used for casting for both the materials.

Roach M (2007)[45] reviewed the base metal alloys used for dental restorations and implants and concluded that Ni-Cr alloys have superior properties for use in porcelain-fused-to-ceramic (PFM) applications. He also observed that the Co-Cr alloys are more corrosion-resistant than the Ni-Cr alloys and have physical properties similar to that of the Ni-Cr alloys. Cast Titanium and its alloys have physical properties which is comparable to that of other base metal alloys. Also titanium and its alloys have excellent biocompatibility and corrosion resistant.

Roberts W et al (2009)[46] in their review article on metal-ceramic alloys in dentistry stated that the increased use of metal-ceramic restorations was the result of their proven history of clinical performance, acceptable esthetics, and satisfactory physical properties. Good clinical performance has been attested to by longitudinal studies that reported that up to 88.7% of metal-ceramic crowns and 80.2% of metal-ceramic fixed partial dentures were still in function after 10 years. He was also in opinion that although considerable function may be borne by the ceramic portion of a metal-ceramic restoration, the success of the entire prosthesis depends largely on the physical properties of the metal substructure.

Watanabe I et al (2009)[57] conducted a study to investigate the effect of laser surface treatment on the mechanical properties of cast titanium. The cast titanium specimens were laser-treated on the surface using a dental Nd:YAG laser machine at 240V and 300V. After laser treatment, tensile testing was conducted to obtain the tensile strength, percent elongation and modulus of elasticity. Results showed that the laser-treated titanium specimens with 300V showed a tensile strength equivalent to the Co–Cr alloy indicating that the laser treatment significantly improved the mechanical properties of cast titanium and they concluded that laser treatment on cast titanium surfaces could produce reliable titanium metal framework for prosthesis.

Machha S et al (2011)[36] conducted a study on microstructure, mechanical performance and corrosion properties of base metal solder joints. Mechanical properties of base metal alloys joined by gas oxygen soldering and laser fusion were compared to a one-piece casting. Mechanical properties evaluated were tensile strength, percentage of elongation and hardness of the solder joint. Results showed that tensile strength of one-piece casting was higher than laser fused and gas oxygen torch soldering joints. Properties of gas oxygen soldered joints were inferior when compared to laser fused joints in both mechanical performance and corrosive properties. They concluded that the laser fused joints have properties between those of one-piece casting and the gas oxygen torch soldering.

Ucar Yurdanur et al (2011)[51] conducted a study to compare the mechanical properties of 6 noble casting alloys. They mentioned that the important mechanical properties necessary for long term performance were 0.1% and 0.2% yield strength, ultimate tensile strength, elastic modulus and percentage elongation.

Bauer J et al (2012)[6] conducted a study to evaluate the tensile strength, elongation, microhardness, microstructure and fracture pattern of various metal ceramic alloys cast under different casting conditions. Two Ni-Cr alloys, Co-Cr and Pd-Ag were used. Results showed that Ni-Cr-Mo alloy had the highest elongation and lowest Vickers microhardness. Regarding tensile strength, Ni-Cr-Be alloy had the highest ultimate tensile strength. They concluded that the composition of the alloys, as well as the casting methods significantly influenced the properties evaluated.

Poulon-Quintin A et al (2012)[43] conducted a study to investigate the effect of laser surface treatment of cast titanium alloy on microstructure and mechanical properties. After the cast surfaces of each specimen were laser treated using a dental Nd:YAG laser machine at 240V and 300 V with and without argon gas shielding, tensile testing and microstructure analysis were conducted. The results of tensile testing and Vickers hardness depth profiling showed that laser treatment improved the mechanical properties. The X-ray diffraction analysis indicated that the beta phase formation was clearly noticeable after laser surface treatment. They concluded that laser treatment on cast titanium surfaces showed significant enhancement of mechanical properties.

MATERIALS AND METHODS

This study was conducted to comparatively evaluate the mechanical properties of base metal alloys and commercially pure titanium with effect of laser surface treatment. The mechanical properties evaluated were hardness, ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation for Ni-Cr, Co-Cr and CP-Ti cast test samples.

The following materials and equipments were used for the study:

Materials used:

1. Nickel-chromium alloy ingots (Bellabond plus,Bego,Germany) (Fig.1)
2. Cobalt-chromium alloy ingots (Wirobond C,Bego,Germany) (Fig.2)
3. Commercially pure titanium(Grade2) ingots(Bio-Ti,Orotig,Italy)(Fig.3)
4. Auto-polymerizing acrylic resin (DPI, India) (Fig.4)
5. Sprue wax (Wachsdraht, Renfert, Germany) (Fig.5)
6. Silicone casting ring (Sili ring, Delta labs, Chennai, India) (Fig.6)
7. Titanium metal casting ring (Dent-care labs, Kerala, India) (Fig.7)
8. Surfactant spray (Auroflim, Bego, Germany) (Fig.8)

9. Phosphate bonded investment material - Powder (Bellasun, Bego, Germany) (Fig.9a) and Liquid (Begosol, Bego, Germany) (Fig.9b)

10. Magnesium oxide based investment material - Powder (Titec Polvere, Orotig, Italy) (Fig.10a) and Liquid (Titec liquido, Orotig, Italy) (Fig.10b)

11. Aluminum oxide powder, 110 μm (Delta labs, Chennai,India) (Fig.11)

12. Carborundum discs (Dentorium, New York, U.S.A.) (Fig.12)

13. Tungsten carbide burs (Sunshine burs, Germany) (Fig.13)

14. Silicon carbide rubber points (Dentsply, Germany) (Fig.14)

15. Bristle brush (Dentsply, Germany) (Fig.15)

16. Alloy polisher (Universal polishing paste,Ivoclar,Switzerland)(Fig.16)

17. Dental occlusal flim (Insight, Kodak, India) (Fig.17)

Equipments employed:

1. Vacuum mixer (Vacuret mini, Reitel, Germany) (Fig.18)

2. Burnout furnace (Technico, TechnicoLaboratory, India) (Fig.19)

3. Burnout furnace (Silfradent, Italy) (Fig.20)

4. Induction casting machine (Fornax, Bego, Germany) (Fig.21)

5. Argon arc melting pressure casting machine (Titec 205 M, Orotig, Italy) (Fig.22)
6. Sandblaster (Delta labs, Chennai, India) (Fig.23)
7. Alloy grinder and polisher (Cutty, Germany) (Fig.24)
8. Dental x-ray unit (Confident, India) (Fig.25)
9. Metallurgical microscope (De-wintor trinocular, Germany) (Fig.26)
10. Micro Vickers Hardness Tester (Wilson Wolpert, Germany) (Fig.28)
11. Tensometer (Associated Scientific Engg. Works, India) (Fig.29)
12. Nd-YAG Laser machine (Lee lasers, U.S.A) (Fig.31)

Description of equipments used:

1. METALLURGICAL MICROSCOPE:

Metallurgical microscope (De-wintor inverted trinocular, Germany) (Fig.26) is the optical microscope, differing from other microscopes in the method of the specimen illumination (Fig.27). Metallurgical microscope was used to observe the micro-structural features of the base metal alloys such as the grains, grain boundaries and dendritic patterns. Since metals are opaque substances they must be illuminated by frontal lighting, therefore the source of light is located within the microscope tube. This is achieved by plain glass reflector, installed in the tube. The image quality and its resolving power are mainly determined by the quality of the objective. The image obtained is magnified by eyepiece in x6, x8 or x10.

2. MICRO VICKERS HARDNESS TESTER:

Vickers hardness tester (Wilson Wolpert – Germany) (Fig.28) is an instrument used to evaluate the microhardness of the metals. The specimens, which were used to test the microhardness, were cleaned and polished at the entire surface. It has a flat table for positioning the specimen for testing. The Vickers indenter tip is used to create indentation for checking the hardness of the sample. The indenter tip is pyramidal in shape and produces diamond shaped indentation. The parameters such as testing load and load distribution time can be programmed in the computer connected to the Vickers hardness tester. The hardness was calculated using the following formula, $VHN=C \times P/L$, P-Applied load in Kgs, L-Length of diagonal, C-Constant for each indenter based on the angle.

3. TENSOMETER:

A tensometer (Associated Scientific Engg. Works, India) (Fig.29) is a device used to determine a material's response to varying strains, called loads.

Tensometer devices consist of two grips that hold a section of test material in place (Fig.30). These grips are then used to apply a tensile or compression force, called a load, to the test piece. Tensometer instruments can create the force through the use of either a screw or a hydraulic arm, which are powered by mechanical or electrical means. It is used to evaluate the Young's modulus (how much it stretches under stress) of a material and other tensile properties of materials, such as ultimate tensile strength, yield strength, modulus of elasticity and percentage elongation. The strain measurements are most commonly measured with an extensometer consisting of electronic sensors connected to a data collection device (often a computer) and software to manipulate and output the data.

4. Nd:YAG LASER MACHINE:

Nd:YAG laser machine (Lee lasers, U.S.A) (Fig.31) is widely used in material processing such as laser metal welding, drilling, engraving and in laser surface treatment (laser peening) of metal. The components of Nd:YAG laser machine are (a) Pump source, (b) Nd:YAG laser crystal and (c) Optics of the Nd:YAG laser. (Fig.32) Flash tubes of krypton flash lamps are used as a pump source to activate the laser crystal. The Nd:YAG laser crystal is approximately 10 cm long and has a diameter of 8 mm. On activation by the pump source, it emits red coloured laser. The laser beam is reflected, amplified and focussed on the subject to be treated by its focusing optics.

METHODOLOGY:

The methodology of this study has been divided into the following stages:

I. **Fabrication of Stainless steel die**

II. **Preparation of Ni-Cr, Co-Cr and CP-Ti cast test samples**

   a. Preparation of the acrylic patterns for casting

   b. Sprue attachment of acrylic patterns

   c. Investing the acrylic patterns

   d. Burnout of acrylic patterns

   e. Casting procedures

   f. Divesting and finishing of cast samples

   g. Grouping of samples

III. **Laser surface treatment of test group samples**

IV. **Microscopic examination of control and test group samples**

V. **Hardness depth profile of control and test group samples**

VI. **Tensile testing of control group samples**

VII. **Tensile testing of test group samples**

I. FABRICATION OF STAINLESS STEEL DIE: (Fig.33-35)

A die was prepared for the fabrication of base metal alloy test specimens. The die was made with stainless steel. The die was a two-piece unit. The upper and lower parts were made with stainless steel. Two rivets were present at the corners of the lower part (Fig.33a) and corresponding holes were present in the upper counterpart (Fig.33b), which fits onto the lower part precisely. A U-shaped slot was given in the side of lower compartment to facilitate separation of the two compartments. Three equal dimensions shaped slots were made according to ISO specification 6871 (Fig.34). The completed mold space dimension were such that three specimens could be obtained at a stretch with the following dimensions: Total length of 42 mm, 8.5 mm length and 6 mm diameter at the gripper surface, 18 mm length and 3 mm diameter at the functional gauge area (Fig.35).

II. PREPARATION OF Ni-Cr, Co-Cr AND CP-Ti CAST TEST SAMPLES: (Fig.36-63)

(a) Preparation of the acrylic patterns for casting: (Fig.36-39)

The patterns were prepared in auto-polymerizing acrylic resin to avoid distortion. A total of 51 acrylic patterns were prepared according to ISO Sp.6871 dimensions and were used for fabricating seventeen (n=17) castings each for Ni-Cr, Co-Cr and CP-Ti.

A thin coat of separating medium was applied all over the components of the metal die on all sides. The slots of the metal die on both upper and lower compartments were filled with auto-polymerizing acrylic resin using sprinkle-on technique (Fig.36). The upper compartment of the metal die was kept into the rivets of the lower compartment and bench pressed (Fig.37). Excess acrylic outside the slots was removed and the material was allowed to set. After poured acrylic came to a plastic stage the metal die was separated (Fig.38a&b) and thus acrylic patterns were obtained after fine trimming and finishing (Fig.39).

(b) Sprue attachment of acrylic patterns: (Fig.40)

For the Ni-Cr, Co-Cr and CP-Ti groups, 17 acrylic patterns each were attached individually to a preformed round wax sprue of 5 mm diameter. The sprue was attached to the base of acrylic pattern at the centre of the gripper surface of dumb bell on each sides which was bent into U-shape and then attached to the base of the crucible former as suggested by ADA Sp.No.38 (Fig.40).

(c) Investing the acrylic patterns: (Fig.41-45)

For the Ni-Cr and Co-Cr groups, Silicone casting ring was positioned over the base of the crucible former (Fig.41). The acrylic patterns were sprayed with surfactant spray (Auroflim, Bego, Germany) to reduce surface tension and to improve wettability (Fig.42). The acrylic patterns for Ni-Cr and Co-Cr groups seventeen (n=17) each were invested using phosphate bonded investment material (Bellasun, Bego,Germany). A 6 mm distance was provided between the acrylic patterns and top of the silicone casting ring (Siliring, Delta, India). As per the manufacture's recommendation, 160 gms of phosphate bonded investment powder is mixed with 30ml of colloidal silica and 8ml of distilled water. Initially the investment was hand mixed thoroughly for 15 seconds and then vacuum mixed for 60 seconds in a mixing unit. Vibrator was used during pouring of the investment material into the casting ring over the patterns to avoid formation of air bubbles (Fig.43). The investment material was allowed to set for 30 minutes after which the silicone casting ring and crucible former was separated from the set invested mould (Fig.44).

For the CP-Ti group, titanium metal casting ring was lined with an cellulose liner having a thickness of 1 mm that was short of the ring at either ends by 3mm. The acrylic patterns for CP-Ti group seventeen (n=17) were invested using magnesium oxide based investment material (Fig.45) following the manufacturer’s recommendation.

(d) Burnout of acrylic patterns: (Fig.46-47)

After 20 minutes of bench cooling, the set investment molds for the Ni-Cr and Co-Cr groups were placed in the burnout furnace (Technico,

Technico Laboratory, India) (Fig.46). Burn out of the acrylic patterns was done using a programmed preheating technique. The investment mold was kept into the furnace at room temperature and was heated continuously up to the temperature of 950^{o} C at the rate of 8^{o}C/min. The investment mold was kept in such a way in the furnace so that the crucible end was in contact with the floor of the furnace for the escape of molten acrylic resin. It was maintained at that final holding temperature of 950^{o} C for 30 mins and casting was done at that same temperature.

For the CP-Ti groups, the molds were placed in burnout furnace (Logic heat, Silfradent, Italy) (Fig.47) at room temperature and was heated up to the temperature of 150^{o} C at the rate of 4^{o}C/min. It was then maintained at that temperature for 60 mins. After the holding time the temperature was gradually raised to 300^{o} C and held at that temperature for 60 mins. It was then heated to maximum temperature of 920^{o} C and maintained for 30 mins. The mold was then gradually cooled to 450^{o} C and maintained at that final temperature for 30 mins and casting was done at 450^{o} C.

The investment molds were kept in such a way in the furnace so that the crucible end was in contact with the floor of the furnace for the escape of molten acrylic resin. The investment mold was reversed later near the end of the burn out cycle with the space hole facing upwards to enable the escape of the entrapped gases and allow oxygen contact to ensure complete burnout of the acrylic patterns.

(e) Casting procedures: (Fig.48-51)

The molds for Ni-Cr and Co-Cr groups were transferred from the burnout furnace to the induction casting machine (Fornax Genu, Germany) (Fig.48) casting procedure was performed quickly to prevent heat loss from the mold resulting in the thermal contraction of the mold. Ni-Cr alloy ingots (Bellabond plus, Bego, Germany) and Co-Cr alloy ingots (Wirobond C, Bego, Germany) were used to cast the molds of their respective groups. The alloy ingots were heated sufficiently till they turned into the molten state. The crucible was then released and the centrifugal force ensured the completion of the casting procedure. Following casting, the hot investment molds were left for bench cooling at room temperature (Fig.49).

For the CP-Ti groups, casting were done in argon arc melting pressure casting machine (Titec F 205M, Orotig, Italy) (Fig.50). The CP-Ti Grade-2 ingots (Bio-ti, Orotig, Italy) were heated sufficiently into the molten state with tungsten electrode under argon atmosphere (Fig.51) and then the grip lifter was switched on and the argon flow pressure of 4.1 bars ensured the completion of the casting procedure.

(f) Divesting and finishing of cast samples: (Fig.52-63)

After cooling, the investment molds were cleaved along its long axis and the casting was left free using sledge hammer (Fig.52). After this the adherent investment was removed from the casting by sandblasting with 110 microns alumina (Delta labs, India) at 80 psi pressure (Fig.53). The sprue was cut and removed with the help of a thin carborundum disc (Dentorium, U.S.A) (Fig.54). Fine trimming was done with tungsten carbide burs (Sunshine burs,Germany) mounted on alloy grinder (Fig.55) and finishing done with silicon carbide rubber points (Dentsply,Germany) (Fig.56). Polishing of the sample was done with alloy polisher (Universal polishing paste, Ivoclar, Switzerland) using bristle brush (Bison brushe, Dentsply, Germany) (Fig.57).

All the samples were finished in a similar manner. Thus seventeen (n=17) cast samples each for Ni-Cr, Co-Cr and CP-Ti were obtained (Fig.58, 59&60). Every sample was subjected to visual inspection for voids, defects or porosity. It was also radiographically examined with the help of dental X-ray unit (Confident, India) using occlusal films (Insight, Kodak, India) for the presence of porosity or defects (Fig.61,62&63). The samples with defects were rejected and new samples were prepared.

(g) Grouping of test samples

A total of seventeen (n=17) cast samples each for Ni-Cr, Co-Cr and CP-Ti were obtained after casting. Six (n=6) untreated samples of Ni-Cr, Co-Cr and CP-Ti each were grouped as Control groups I, II and III respectively. The remaining eleven (n=11) samples of Ni-Cr, Co-Cr and CP-Ti each were grouped as Test groups I, II and III respectively. The test group samples were subjected to laser surface treatment (laser peening).

III. LASER SURFACE TREATMENT OF TEST GROUP SAMPLES: (Fig.64-65)

11 samples each from test group I (Ni-Cr), test group II (Co-Cr) and test group III (CP-Ti) were subjected to laser surface treatment in order to determine the effects of laser surface treatment on the mechanical properties of base metal alloys. Laser surface treatment was performed using a dental Nd:YAG laser welding machine (Lee lasers, Q-switched, U.S.A) using the following parameters for all the three groups: spot diameter of 1.2 mm, pulse duration of 10 ms, frequency of 1.1 Khz and fluence value of 450 J/Cm^2. Each sample was mounted on a customised jig which allowed the sample to be rotated manually in slow rpm in order to treat the sample uniformly on the functional gauge area (Fig.64). The laser beam was detected and observed using infra - red camera and used to position the laser on top of the sample's functional gauge area. During the laser treatment, high pressure argon gas

shielding was applied from one nozzle set at a 45^{o} angle above the treatment area of the sample (Fig.65). Laser single pulses were applied perpendicular to the long axis of each sample linearly in order to avoid misshaping of the straight gauge due to the induction of compressive stresses by the laser. After uniform laser treatment on the functional gauge area of the sample, the sample was then allowed to cool to room temperature and stored in clean container to keep it ready for tensile testing. The same was repeated for all the 11 test samples from each group. One sample treated with laser surface treatment was observed with metallurgical microscope and subjected to Vickers micro hardness testing. The remaining 10 samples were subjected to tensile testing.

IV. MICROSCOPIC EXAMINATION OF CONTROL AND TEST GROUP SAMPLES: (Fig.66-73)

Cross section of one (n=1) untreated Control group samples of Ni-Cr, Co-Cr and CP-Ti samples (Control groups I, II and III) and cross section of one (n=1) Test group samples of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II and III) respectively was prepared for microscopic examination. These samples were prepared by embedding in bakelite and ground to a smooth surface using silicon carbide paper upto 320 grit. Final polishing was completed with alumina paste, followed by chemical etching in a mixture of water, nitric acid and hydrofluoric acid (85:10:5 in volume). The cross section of the prepared sample (Fig.66) from each group was observed using metallurgical microscope (Fig.67). Metallurgical microscopic images of these representative samples were captured by using metallurgical microscope (Fig.68-73)

V. HARDNESS DEPTH PROFILE OF CONTROL AND TEST GROUP SAMPLES: (Fig.74)

Hardness testing was done in order to determine the Vickers microhardness of as-cast samples and samples subjected to laser surface treatment. Cross section of one (n=1) untreated Control group samples of Ni-Cr, Co-Cr and CP-Ti (Control groups I, II and III) and cross section of one (n=1) Test group samples of Ni-Cr, Co-Cr and CP-Ti after laser peening (Test groups I, II and III) respectively was subjected to Vickers microhardness measurements with 0.5 kg load using a microhardness tester (Wilson Wolpert – Germany) (Fig.74). A total of ten measurements started from the cast surface to 450 µm in depth with 50 µm increments were noted. The results were then tabulated.

VI. TENSILE TESTING OF CONTROL GROUP SAMPLES: (Fig.75-76)

Tensile testing was done in order to evaluate the mechanical properties such as ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation.

5 untreated samples (n=5) of Ni-Cr, Co-Cr and CP-Ti samples (Control groups I, II and III) respectively were subjected to tensile testing.

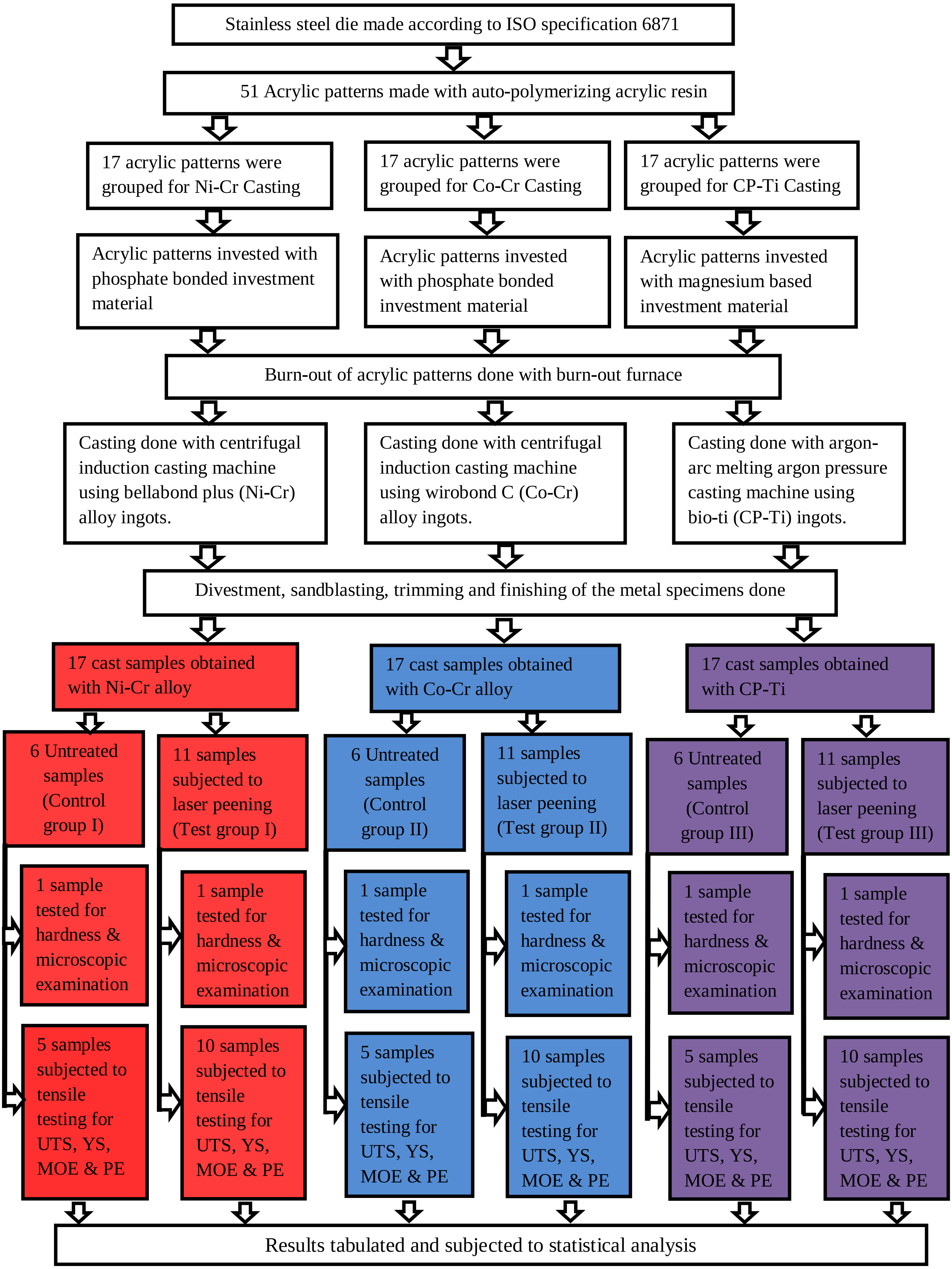
Each control sample was placed in the custom made securing device that can be engaged in the tensometer (Associated Scientific Engineering Works, New Delhi, India) (Fig.75). An incremental tensile load of 0.1 KN per minute was applied with cross head speed of 0.5mm per minute. Load was applied until the sample was fractured (Fig.76). The strain measurements were measured with an extensometer consisting of electronic sensors connected to a computer and software to manipulate and output the data. The values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation were displayed and recorded for each sample. The results were tabulated. The same was repeated for all the 15 control samples (n=5 Ni-Cr, n=5 Co-Cr & n=5 CP-Ti).

VII. TENSILE TESTING OF TEST GROUP SAMPLES: (Fig.77-78)

Ten (n=10) each of Ni-Cr, Co-Cr and CP-Ti laser treated samples (Test groups I, II and III respectively) were subjected to tensile testing.

The tensile testing of test group sample (Fig.77-78) was done in a similar manner as done previously for the control group sample. The same was repeated for all the 30 test samples (n=10 Ni-Cr, n=10 Co-Cr & n=10 CP-Ti).

METHODOLOGY – OVERVIEW



MATERIALS

Fig: 1 Ni-Cr alloy ingots

Fig: 2 Co-Cr alloy ingots

Fig: 3 CP-Ti (Grade 2) ingots

Fig: 4 Auto-polymerizing acrylic resin

Fig: 5 Sprue wax

Fig: 6 Silicone casting ring

Fig: 7 Titanium metal casting ring

Fig: 8 Surfactant spray

Fig: 9 Phosphate bonded investment material – (a) Powder & (b) Liquid

Fig:10 Magnesium oxide based investment material – (a) Powder & (b) Liquid

Fig: 11 Aluminum oxide powder

Fig: 12 Carborundum disc

Fig: 13 Tungsten carbide burs

Fig: 14 Silicon carbide rubber points

Fig: 15 Bristle brushes

Fig: 16 Alloy polishing paste

Fig: 17 Dental occlusal film

EQUIPMENTS

Fig: 18 Vacuum mixer

Fig: 19 Burnout furnace (For Ni-Cr & Co-Cr groups)

Fig: 20 Burnout furnace for CP-Ti

Fig: 21 Induction casting machine

Fig: 22 Argon arc melting pressure casting machine

Fig: 23 Sandblaster

Fig: 24 Alloy grinder & polisher

Fig: 25 Dental x-ray unit

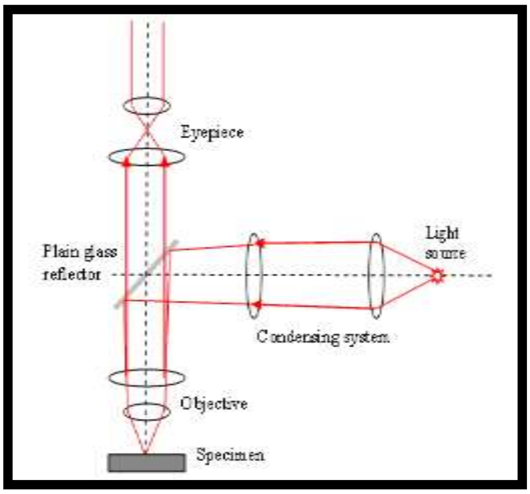
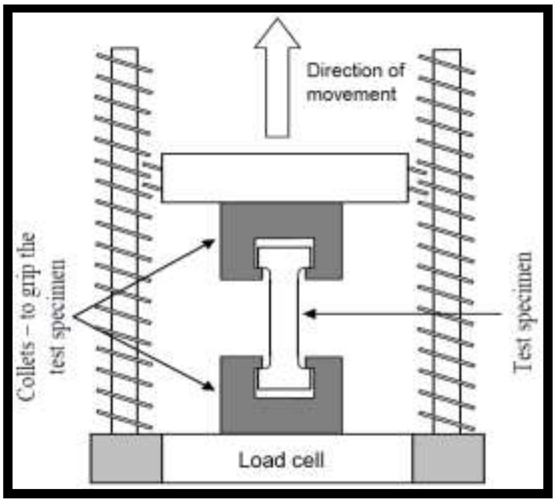


Fig: 26 Metallurgical microscope

Fig: 27 Optical layout of Metallurgical microscope

Fig: 28 Micro Vickers Hardness Tester

Fig: 29 Tensometer



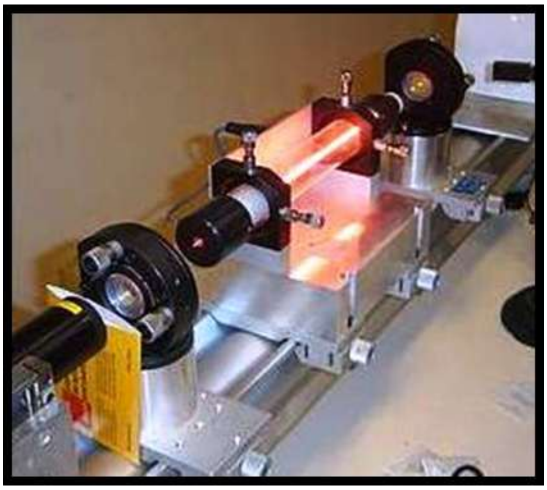


Fig:30 Schematic representation of Tensometer

Fig: 31 Nd-YAG laser machine

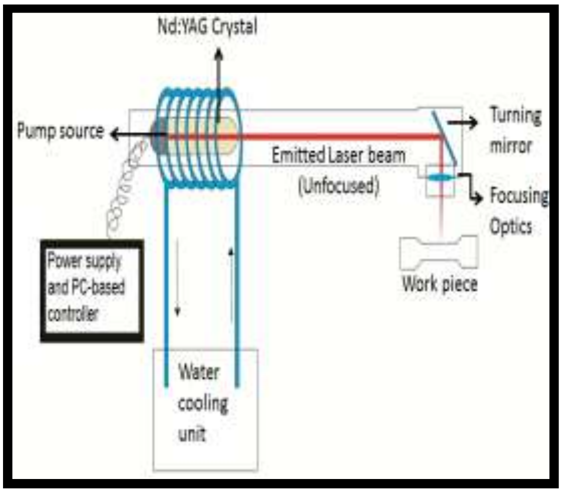


Fig: 32 Schematic representation of Nd-YAG laser machine

METHODOLOGY

I. FABRICATION OF STAINLESS STEEL METAL DIE

Fig: 33 (a) & (b): Stainless steel die

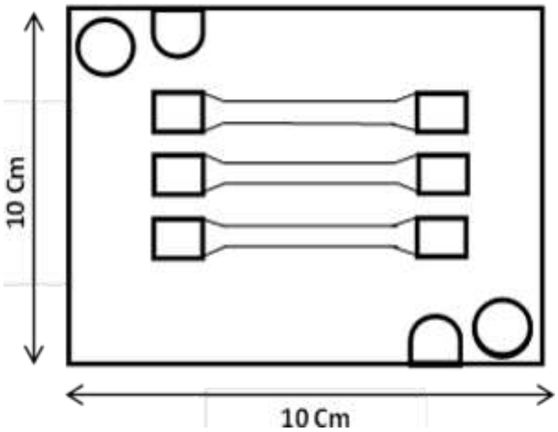


Fig: 34 Dimensions of the stainless steel die

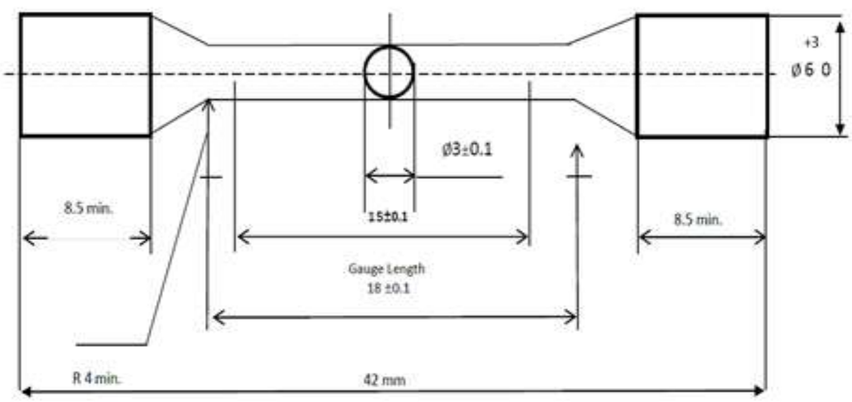


Fig: 35 Dimensions of the cast test samples

II. PREPARATION OF Ni-Cr, Co-Cr AND CP-Ti CAST TEST SAMPLES

Fig: 36 Filling of slots of die with auto-polymerizing acrylic resin

Fig: 37 Bench pressing of patterns in stainless steel die

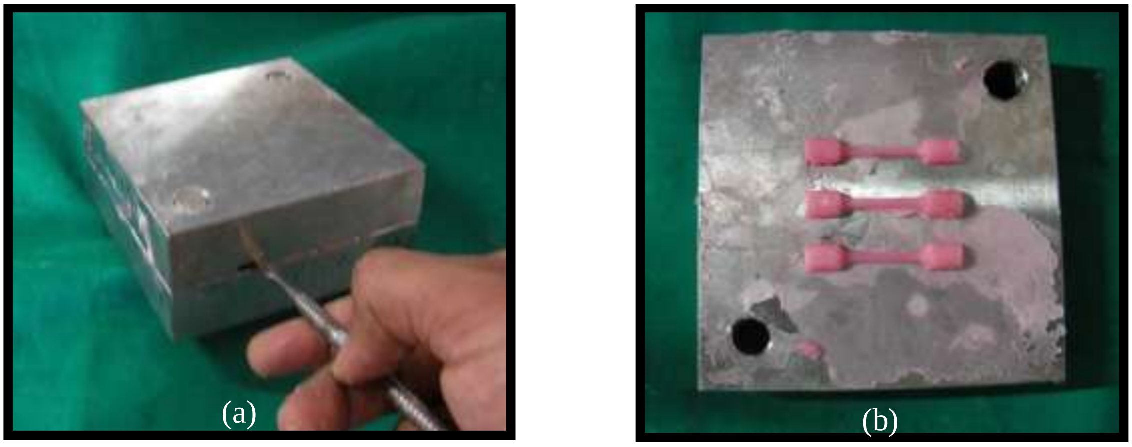


Fig: 38 (a) &(b) Separation of acrylic patterns from metal die

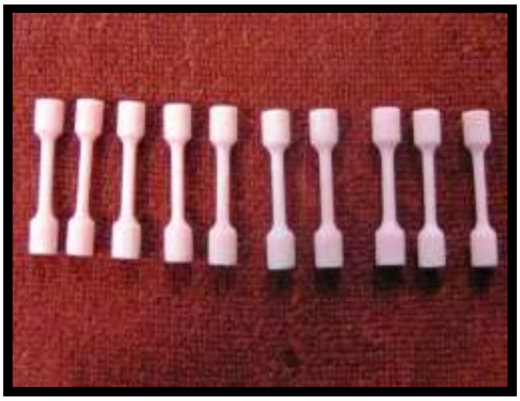


Fig: 39 Finished acrylic patterns

Fig: 40 Sprue attached to the acrylic patterns

Fig: 41 positioning of silicone casting ring

Fig: 42 Patterns sprayed with surfactant

Fig: 43 Investing the patterns for Ni-Cr and Co-Cr group using Silicone casting ring

Fig: 44 Set invested mold

Fig: 45 Investing the patterns for CP-Ti Group using titanium metal casting ring

Fig: 46 Mold placed in burnout furnace (Ni-Cr and Co-Cr groups)

Fig: 47 Mold placed in burnout furnace (CP-Ti groups)

Fig: 48 Mold placed in induction casting machine (Ni-Cr and Co-Cr groups)

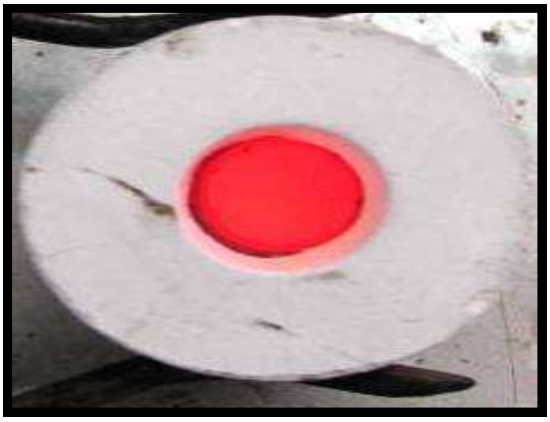


Fig: 49 Bench cooling of mold after casting

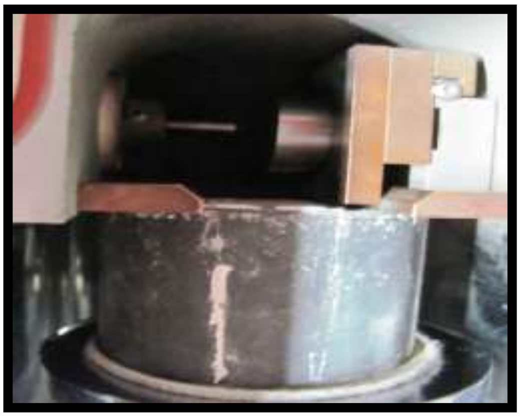


Fig: 50 CP-Ti casting done in Argon arc melting pressure casting machine

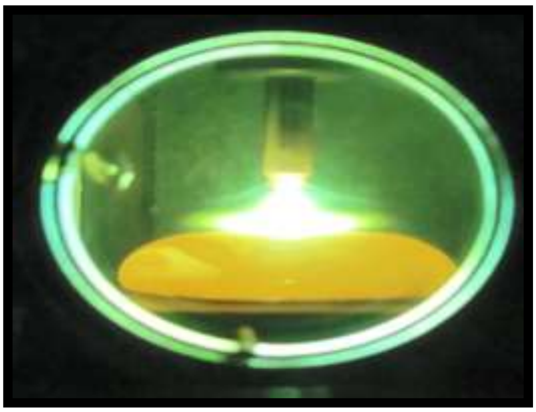


Fig: 51 CP-Ti Ingot heated under argon atmosphere

Fig: 52 Divesting of castings

Fig: 53 Sandblasting the sample

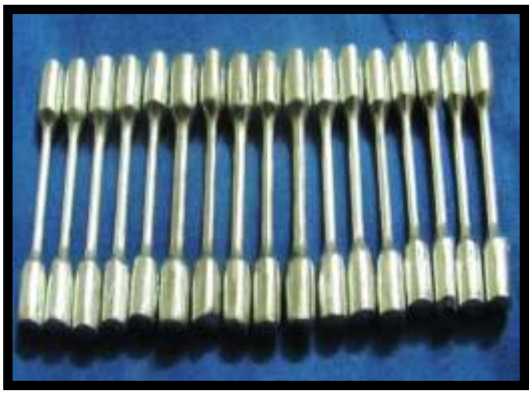
Fig: 54 Sprue cut using Carborundum disc

Fig: 55 Trimming of sample with tungsten carbide bur

Fig: 56 Finishing of sample using silicone carbide rubber points

Fig: 57 Polishing the sample

Fig: 58 Finished Ni-Cr samples



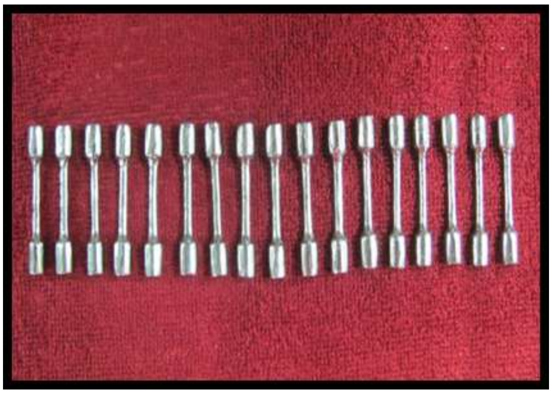
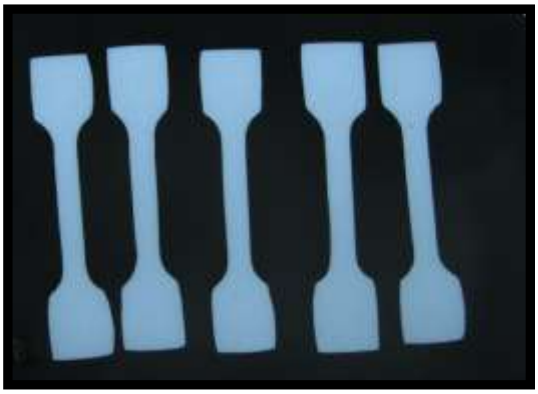


Fig: 59 Finished Co-Cr samples

Fig: 60 Finished CP-Ti samples



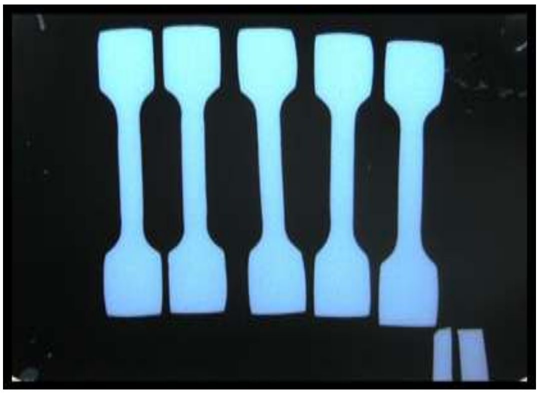


Fig: 61 Radiographic inspection of Ni-Cr samples for defects

Fig: 62 Radiographic inspection of Co-Cr samples for defects

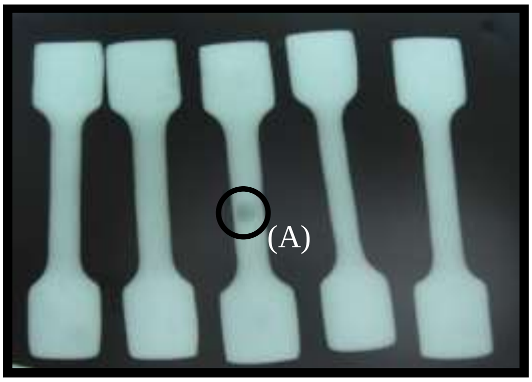


Fig: 63 Radiographic inspection of CP-Ti samples for defects
Discarded sample due to defect (A)

III. Laser surface treatment of test group samples

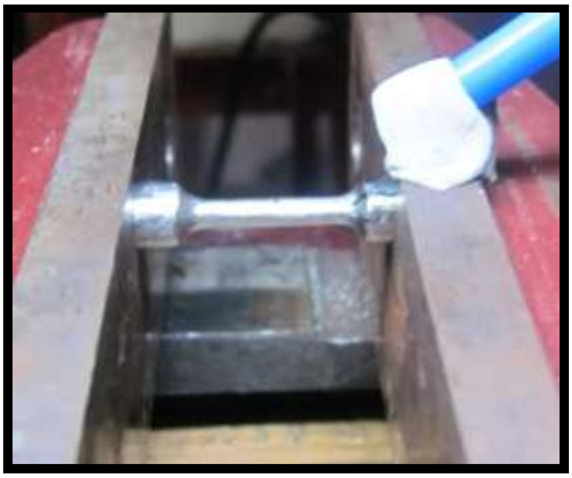


Fig: 64 Sample mounted on a customised jig

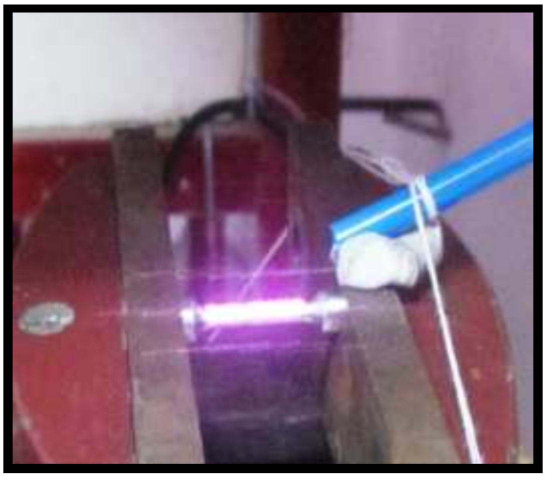


Fig: 65 Argon gas shielding during laser Treatment

IV. Microscopic examination of one representative sample of all control and test groups

Fig: 66 Prepared sample for microscopic examination

Fig: 67 Microscopic examination of sample

Fig: 68 Metallurgical microscopic image of untreated Ni-Cr sample

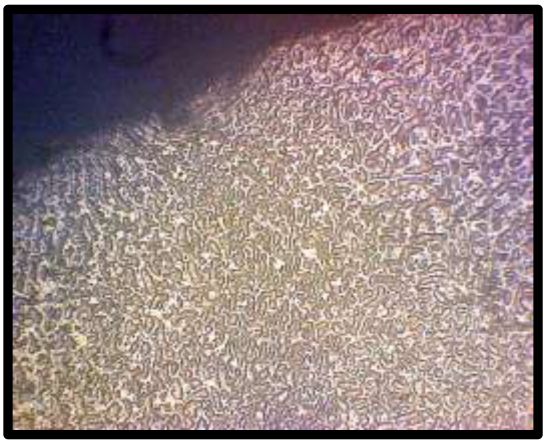


Fig: 69 Metallurgical microscopic image of laser treated Ni-Cr sample

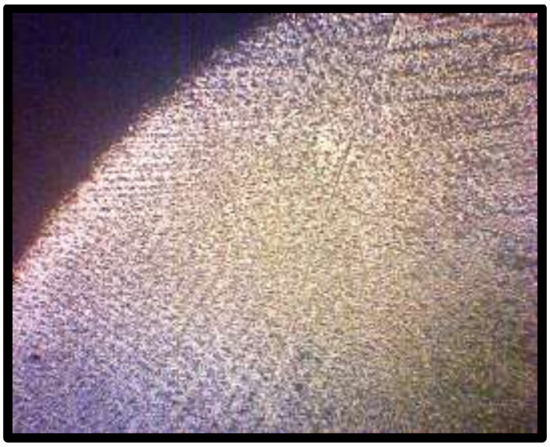


Fig: 70 Metallurgical microscopic image of untreated Co-Cr sample

Fig: 71 Metallurgical microscopic image of laser treated Co-Cr sample

Fig: 72 Metallurgical microscopic image of untreated CP-Ti sample

Fig: 73 Metallurgical microscopic image of laser treated CP-Ti sample

V. Hardness depth profile of one representative sample of all control and test groups

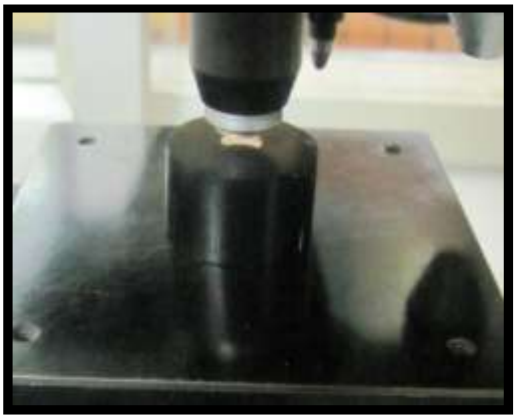


Fig: 74 Measurement of Vickers microhardness

VI. Tensile testing of Control group samples

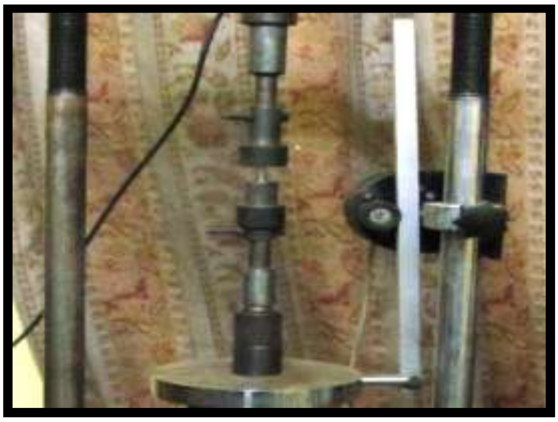


Fig: 75 Control samples engaged in the tensometer

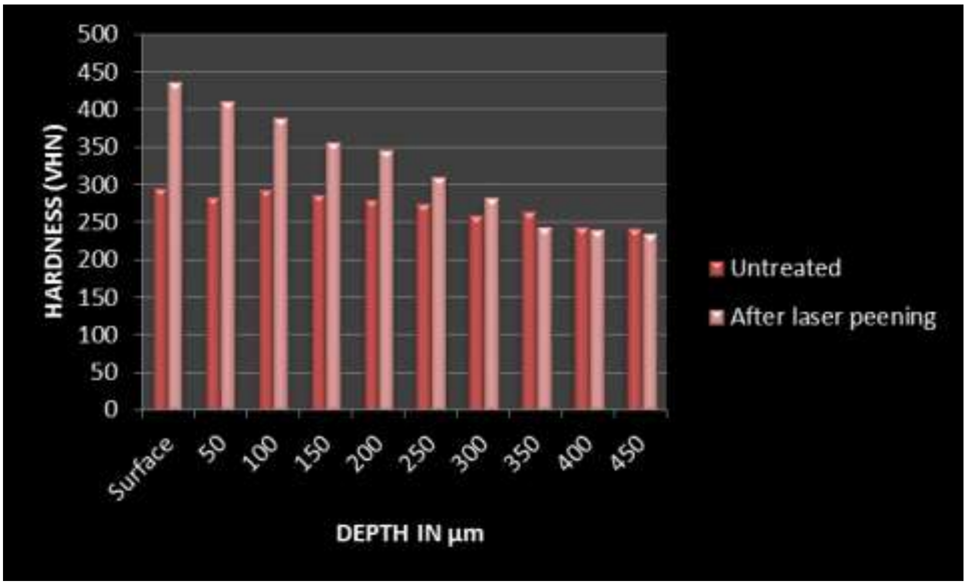
Fig: 76 Fractured control samples

VII. Tensile testing of Test group samples

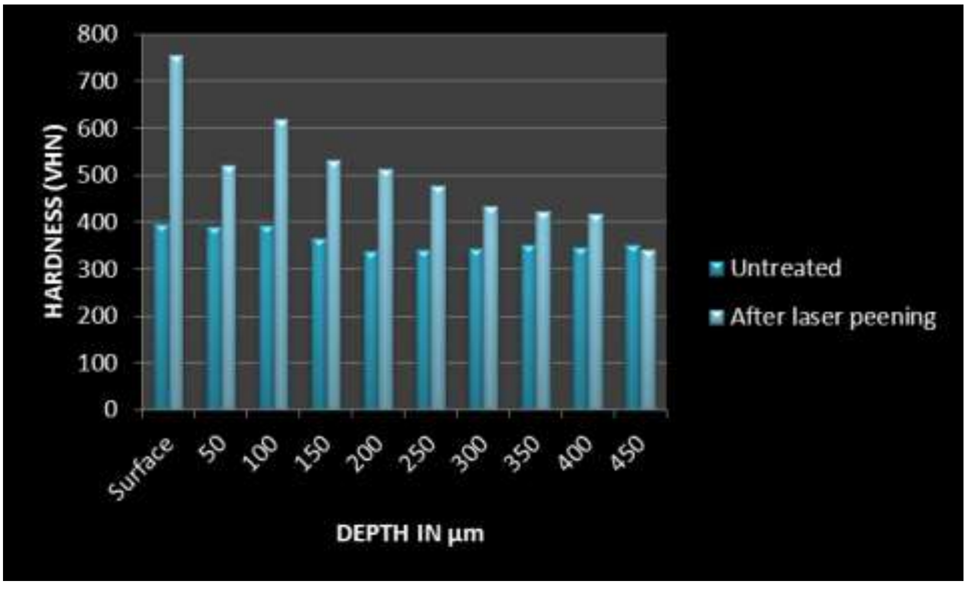
Fig: 77 Test samples engaged in the tensometer

Fig: 78 Fractured test samples

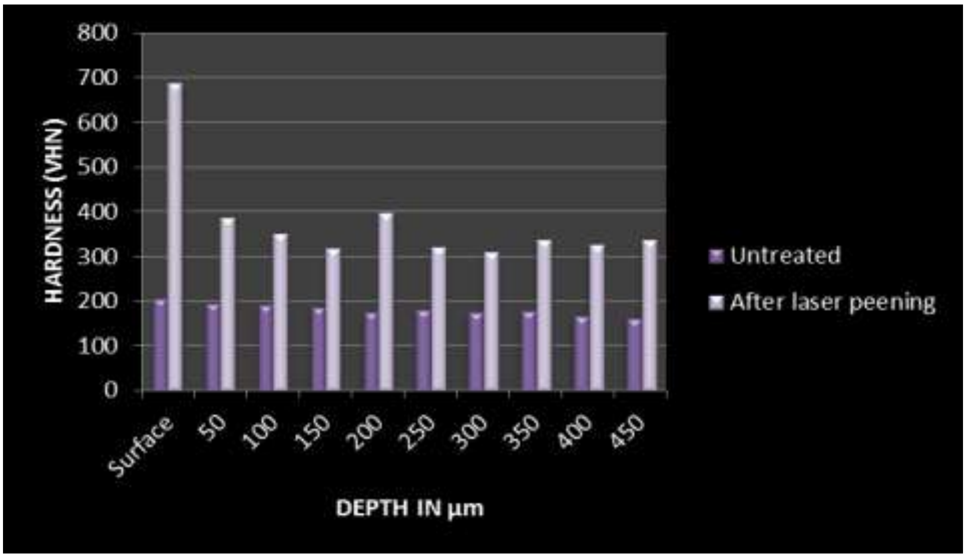
Graph 1: Hardness depth profile of Ni-Cr samples before (Control group I) and after laser peening (Test group I)



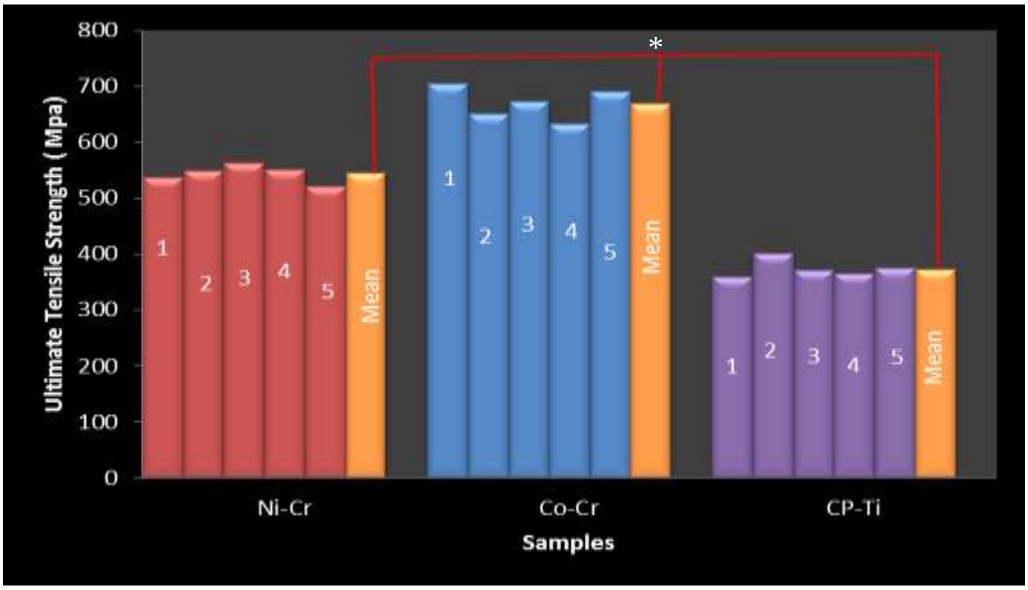
Graph 2: Hardness depth profile of Co-Cr samples before (Control group II) and after laser peening (Test group II)



Graph 3: Hardness depth profile of CP-Ti samples before (Control group III) and after laser peening (Test group III)

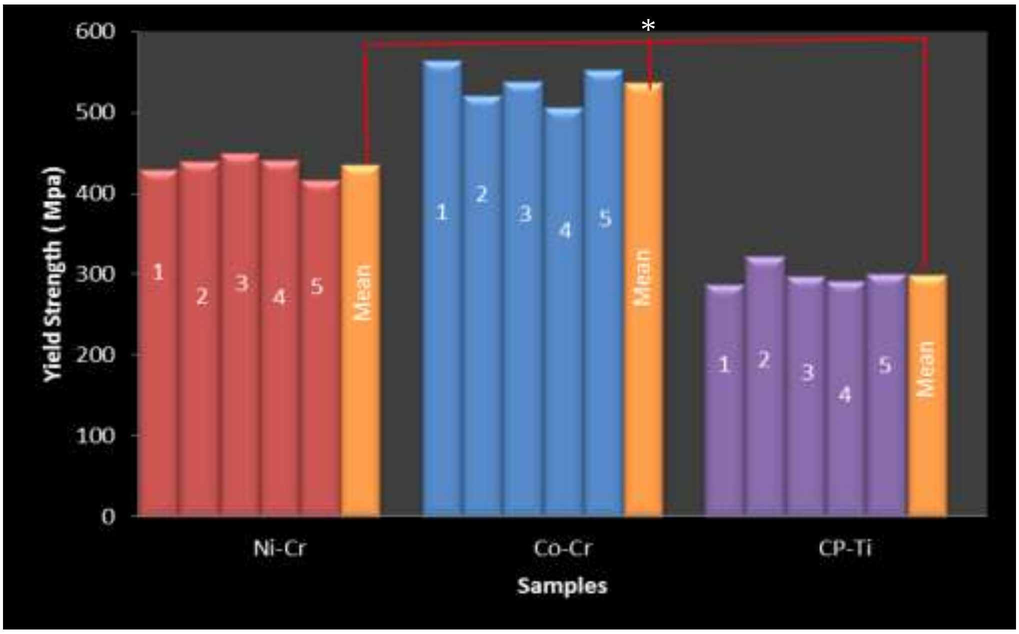


Graph 4: Basic values and Comparison of means of Ultimate Tensile Strength of untreated Ni-Cr, Co-Cr and CP-Ti samples (Control groups I, II & III)



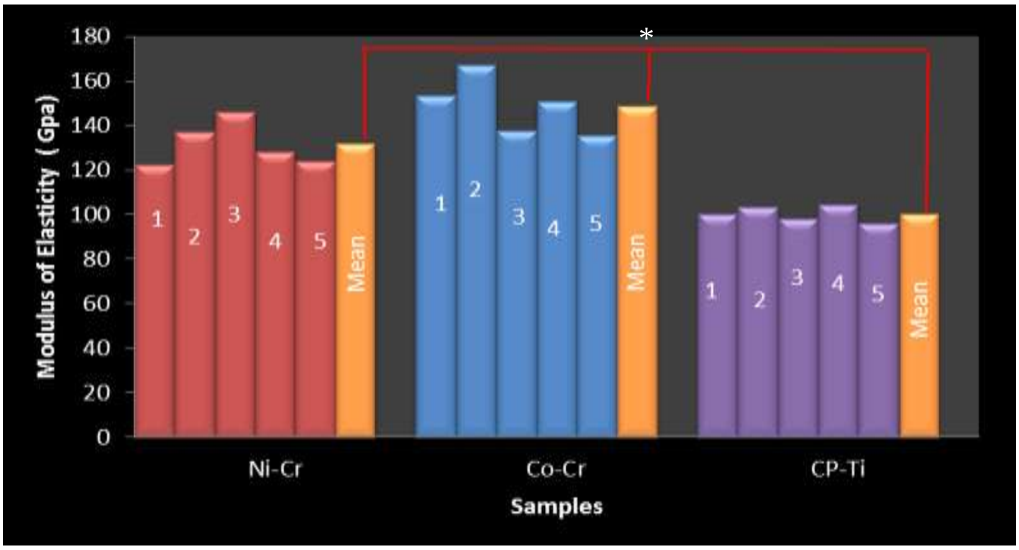
Note: * The mean difference is significant at the 0.05 level.

Graph 5: Basic values and Comparison of means of Yield Strength of untreated Ni-Cr, Co-Cr and CP-Ti samples (Control groups I, II & III)



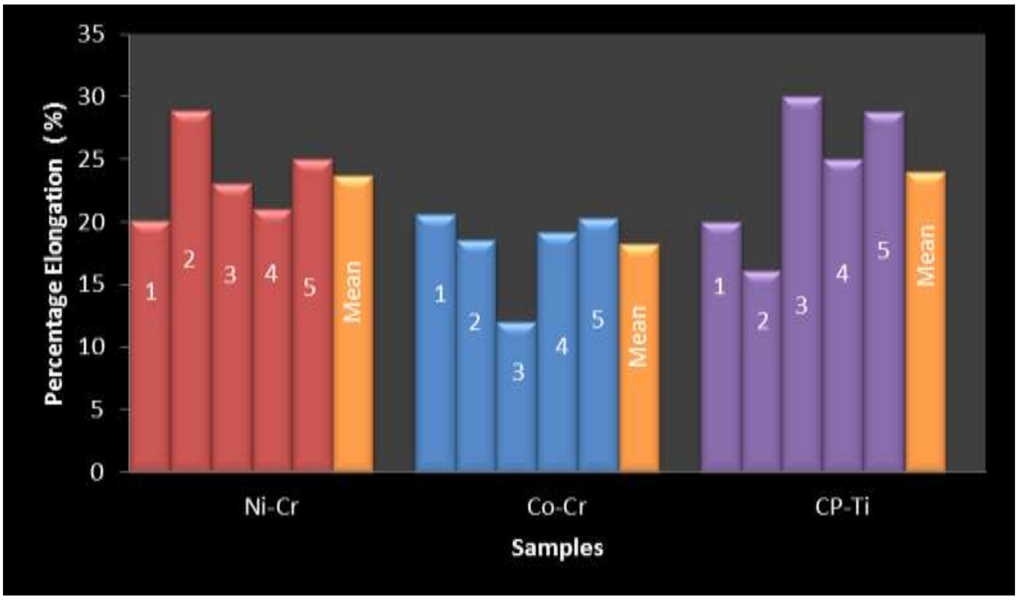
Note: * The mean difference is significant at the 0.05 level.

Graph 6: Basic values and Comparison of Modulus of Elasticity of untreated Ni-Cr, Co-Cr and CP-Ti samples (Control groups I, II & III)

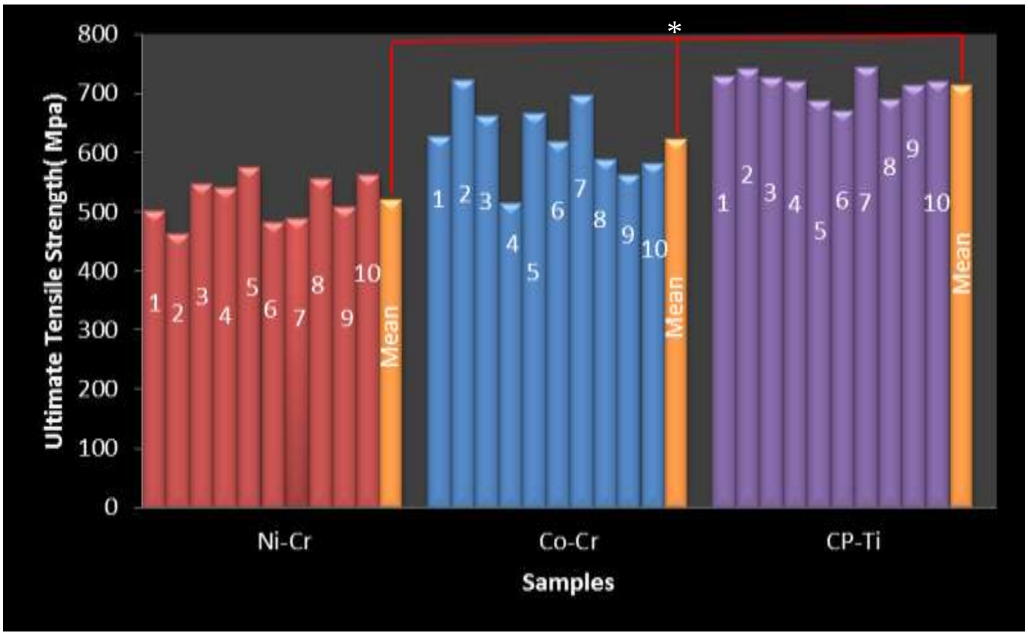


Note: * The mean difference is significant at the 0.05 level.

Graph 7: Basic values and Comparison of Percentage Elongation of untreated Ni-Cr, Co-Cr and CP-Ti samples (Control groups I, II & III)

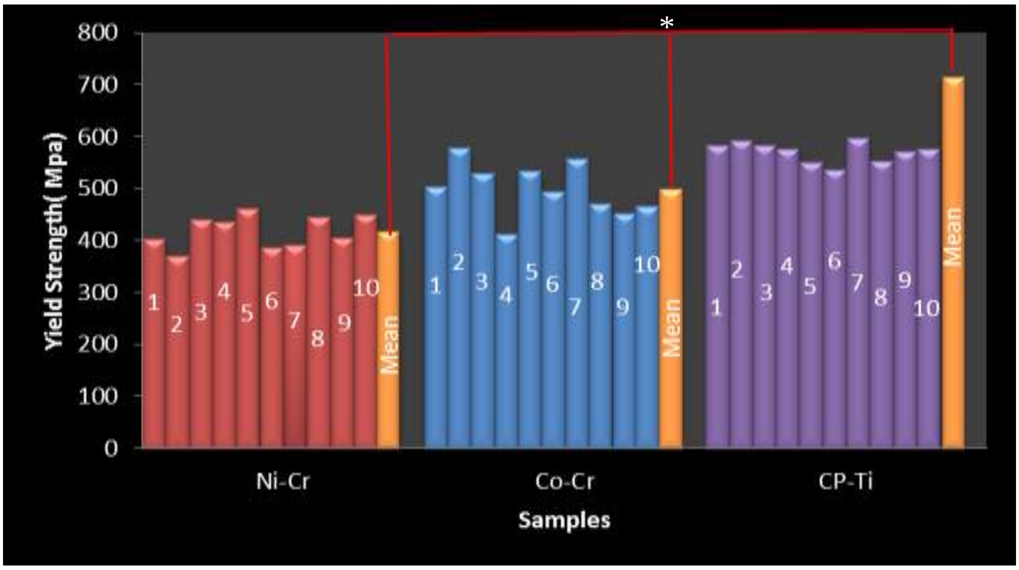


Graph 8: Basic values and comparison of Ultimate Tensile Strength of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)



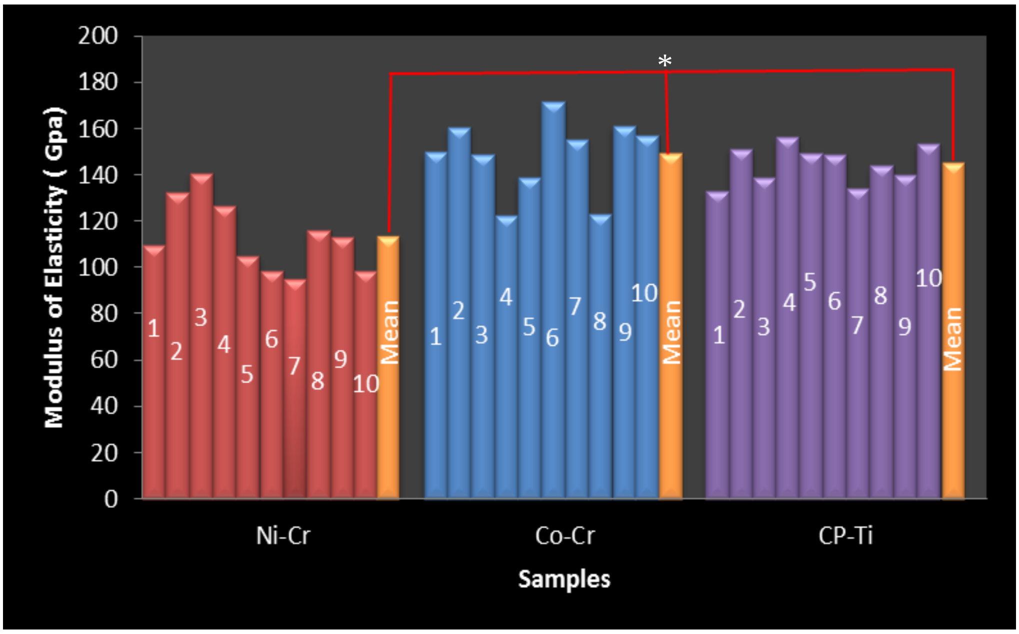
Note: * The mean difference is significant at the 0.05 level.

Graph 9: Basic values and Comparison of Yield strength of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)



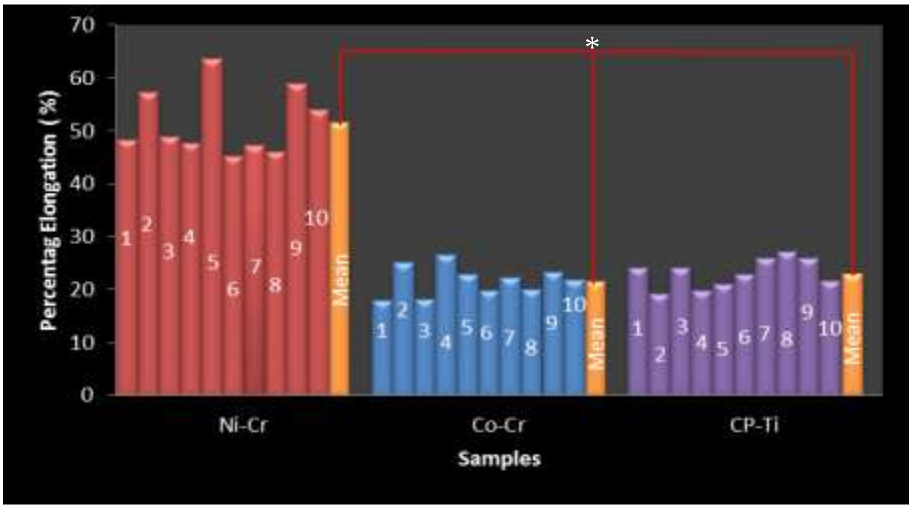
Note: * The mean difference is significant at the 0.05 level.

Graph 10: Basic values and Comparison of Modulus of Elasticity of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)



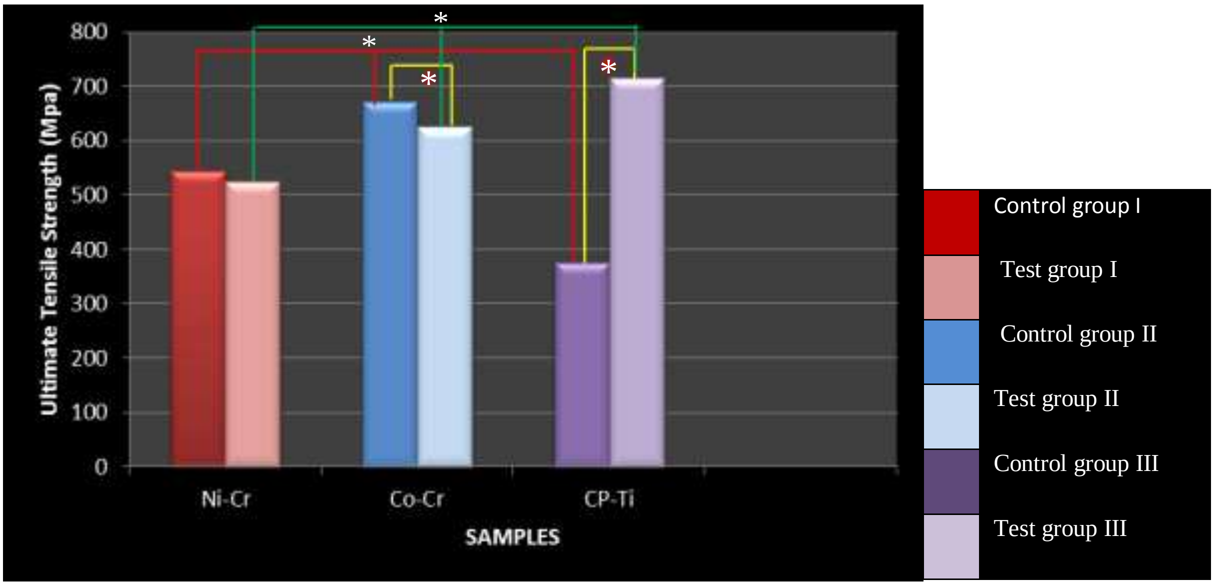
Note: * The mean difference is significant at the 0.05 level.

Graph 11: Basic values and Comparison of Percentage Elongation of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)



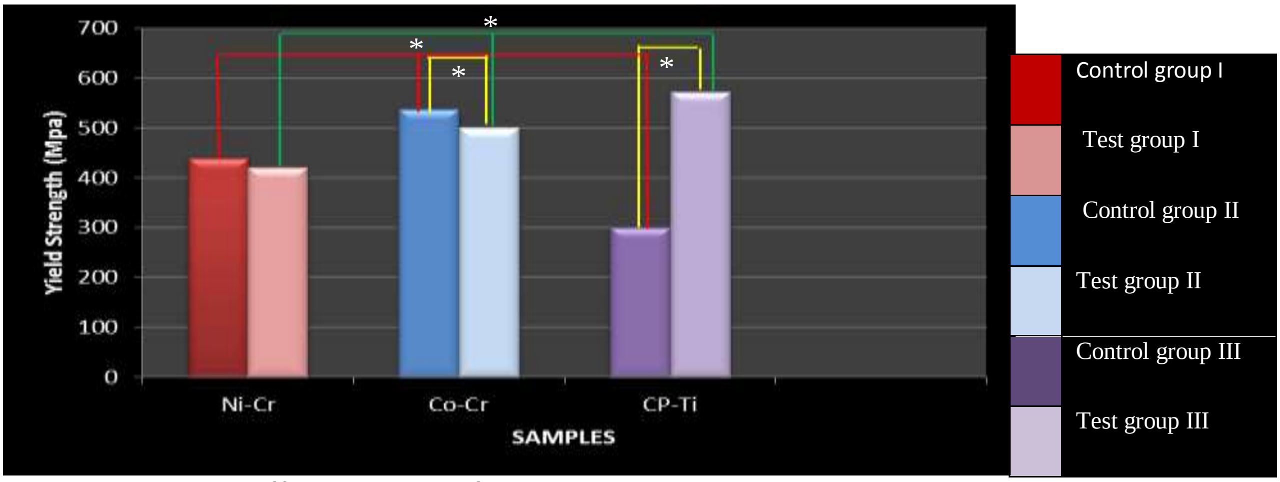
Note: * The mean difference is significant at the 0.05 level.

Graph 12: Comparison of means of Ultimate Tensile Strength of Ni-Cr, Co-Cr and CP-Ti samples before (Control groups I, II & III) and after laser peening (Test groups I, II & III)



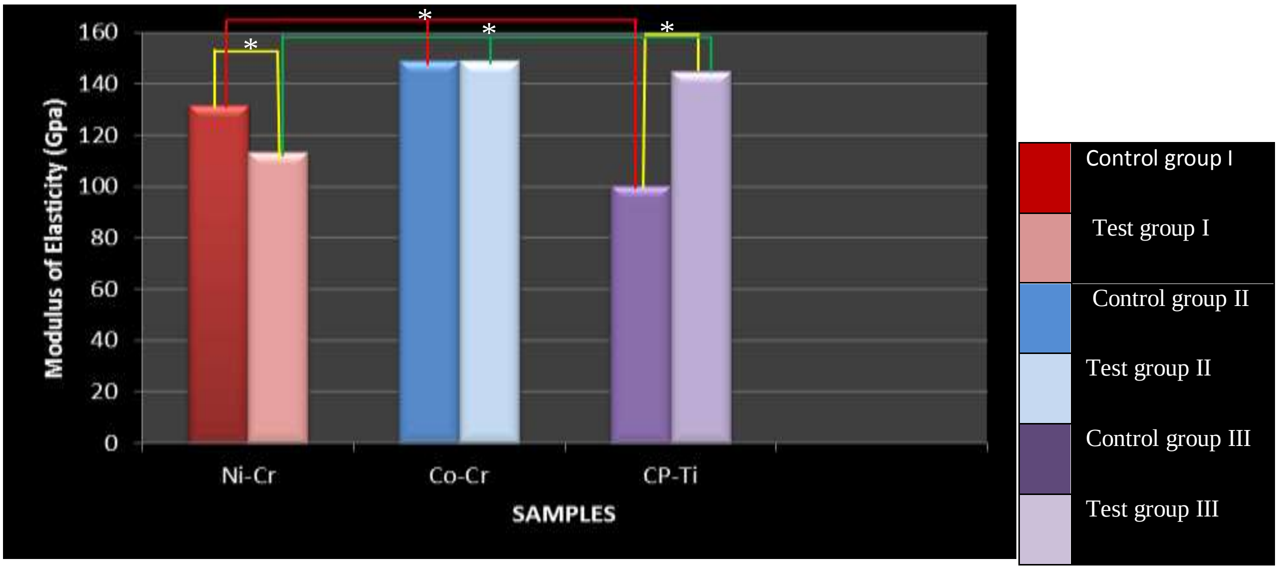
Note: * The mean difference is significant at the 0.05 level

Graph 13: Comparison of means of Yield Strength of Ni-Cr, Co-Cr and CP-Ti samples before (Control groups I, II & III) and after laser peening (Test groups I, II & III)



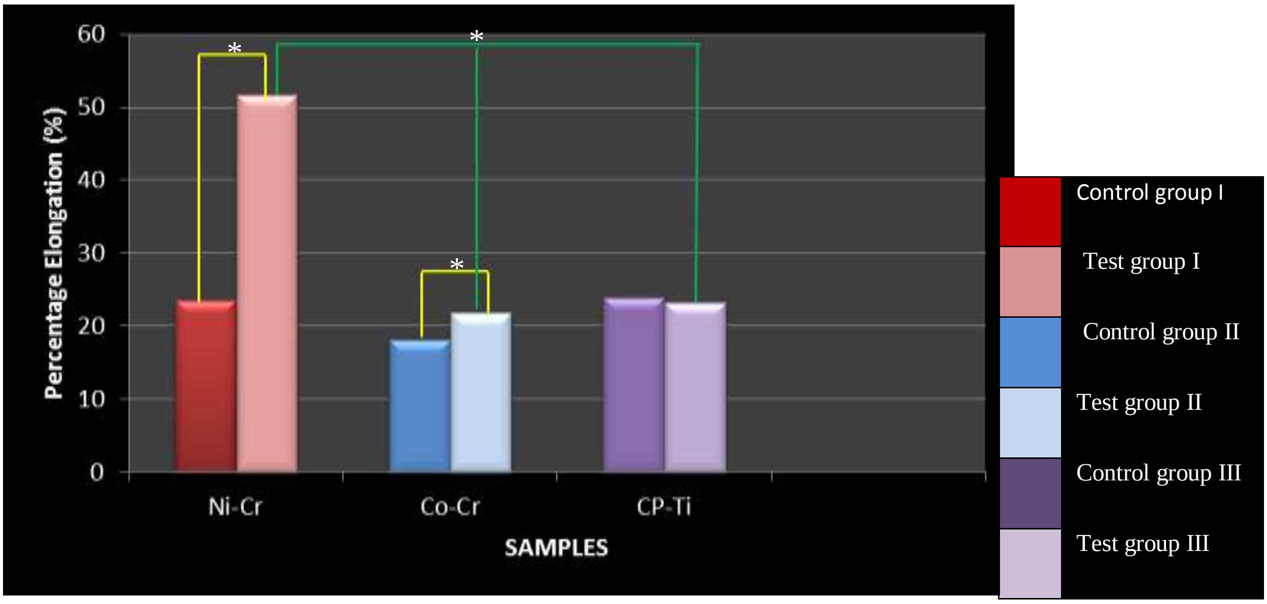
Note: * The mean difference is significant at the 0.05 level.

Graph 14: Comparison of means of Modulus of Elasticity of Ni-Cr, Co-Cr and CP-Ti samples before (Control groups I, II & III) and after laser peening (Test groups I, II & III)



Note: * The mean difference is significant at the 0.05 level.

Graph 15: Comparison of means of Percentage Elongation of Ni-Cr, Co-Cr and CP-Ti samples before (Control groups I, II & III) and after laser peening (Test groups I, II & III)



Note: * The mean difference is significant at the 0.05 level.

RESULTS

The present in vitro study was conducted to comparatively evaluate the mechanical properties of base metal alloys and commercially pure titanium with effect of laser surface treatment.

The following results were obtained from the study which compared the mechanical properties namely Hardness, Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation between Ni-Cr, Co-Cr and CP-Ti samples before (Control groups) and after laser peening (Test groups). Mean and standard deviation (S.D) of all the values for each group were obtained and they were statistically analysed by using one way ANOVA, Post hoc Tukey HSD test and one sample T-test.

Table 1 shows the Hardness depth profile of Ni-Cr, Co-Cr and CP-Ti samples before (Control groups I, II & III) and after laser peening (Test groups I, II & III)

Table 2 shows the basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Ni-Cr samples before laser peening (Control group I)

Table 3 shows the basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Co-Cr samples before laser peening (Control group II)

Table 4 shows the basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of CP-Ti samples before laser peening (Control group III)

Table 5 shows the basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Ni-Cr samples after laser peening (Test group I)

Table 6 shows the basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Co-Cr samples after laser peening (Test group II)

Table 7 shows the basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of CP-Ti samples after laser peening (Test group III)

Table 8 shows the comparison of Surface Hardness of Ni-Cr, Co-Cr and CP-Ti samples before and after laser peening

Table 9 shows the comparison of means of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Ni-Cr samples before (Control group I) and after laser peening (Test group I)

Table 10 shows the comparison of means of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Co-Cr samples before (Control group II) and after laser peening (Test group II)

Table 11 shows the comparison of means of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of CP-Ti samples before (Control group III) and after laser peening (Test group III)

Table 12 shows the comparison of means of Ultimate tensile strength of Ni-Cr, Co-Cr and CP-Ti samples before laser peening (Control groups I, II & III)

Table 13 shows the comparison of means of Yield strength of Ni-Cr, Co-Cr and CP-Ti samples before laser peening (Control groups I, II & III)

Table 14 shows the comparison of means of modulus of elasticity of Ni-Cr, Co-Cr and CP-Ti samples before laser peening (Control groups I, II & III)

Table 15 shows the comparison of means of Percentage of elongation of Ni-Cr, Co-Cr and CP-Ti samples before laser peening (Control groups I, II & III)

Table 16 shows the comparison of means of Ultimate tensile strength of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)

Table 17 shows the comparison of means of Yield strength of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)

Table 18 shows the comparison of means of Modulus of elasticity of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)

Table 19 shows the comparison of means of Percentage of elongation of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)

Table 1: Hardness depth profile of Ni-Cr, Co-Cr and CP-Ti samples before (Control groups I, II &III) and after laser peening (Test groups I, II &III)

Depth in µm	Hardness (VHN)					
	Ni-Cr		Co-Cr		CP-Ti	
	Untreated	After laser peening	Untreated	After laser peening	Untreated	After laser peening
Surface	295.3	437	394	754.3	205.2	689
50	283.2	410.5	390.1	521.4	194	388
100	293.1	389.8	392.5	620.2	190.2	352
150	287.4	357.3	365	530.7	185	319
200	280.1	346.9	336.6	512.1	176.4	398
250	275	310.5	340.1	477.4	180.7	323
300	259.1	283.3	342	433.3	174	312
350	264	245	350.4	423.5	176.8	339
400	245	240	346.9	416	167	327
450	242.1	236	351	340	162.4	338.2

INFERENCE:

The surface hardness of the test group sample was much higher than that of untreated sample and it gradually decreased to value similar to control group at a depth of 400 µm for Ni-Cr and at a depth of 450 µm for Co-Cr. The surface hardness of the CP-Ti test group sample was more than three times that of untreated sample. Even at 450 µm depth the hardness of laser treated sample was almost twice the value of the untreated sample for CP-Ti.

Table 2: Basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Ni-Cr samples before laser peening (Control group I)

Sample No	Ultimate tensile strength (Mpa)	Yield strength 0.2% (Mpa)	Elastic modulus (Gpa)	Elongation (%)
1	538	430.4	122.27	20
2	550	440	137.50	29
3	564	451.2	146.49	23
4	552	441.6	128.37	21
5	522	417.6	124.29	25
Mean/S.D	**545.2/±15.91**	**435.88/±12.83**	**131.78/±10.09**	**23.6/±3.58**

INFERENCE:

For the untreated Ni-Cr samples (Control group I), the basic mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation were found to be 545.2 Mpa, 435.88 Mpa, 131.78 Gpa and 23.6 % respectively.

Table 3: Basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Co-Cr samples before laser peening (Control group II)

Sample No	Ultimate tensile strength (Mpa)	Yield strength 0.2% (Mpa)	Elastic modulus (Gpa)	Elongation (%)
1	705	564	153.26	20.6
2	652	521.6	167.18	18.6
3	674	539.2	137.55	12
4	634	507.2	150.95	19.2
5	690.2	552.5	135.33	20.3
Mean/S.D	**671.04/±28.56**	**536.9/±22.91**	**148.85/±12.96**	**18.14/±3.53**

INFERENCE:

For the untreated Co-Cr samples (Control group II), the basic mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation were found to be 671.04 Mpa, 536.9 Mpa, 148.85 Gpa and 18.14 % respectively.

Table 4: Basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of CP-Ti samples before laser peening (Control group III)

Sample No	Ultimate tensile strength (Mpa)	Yield strength 0.2% (Mpa)	Elastic modulus (Gpa)	Elongation (%)
1	360.2	288	100.06	20
2	402.4	322	103.18	16.1
3	372.1	297.7	97.92	30
4	365.3	292.2	104.37	25
5	375.2	300.5	96.21	28.8
Mean/S.D	**375.04/±16.37**	**300.08/±13.18**	**100.35/±3.44**	**23.98/±5.88**

INFERENCE:

For the untreated CP-Ti samples (Control group III), the basic mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation were found to be 375.04 Mpa, 300.08 Mpa, 100.35 Gpa and 23.98 % respectively.

Table 5: Basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Ni-Cr samples after laser peening (Test group I)

Sample No	Ultimate tensile strength (Mpa)	Yield strength 0.2% (Mpa)	Elastic modulus (Gpa)	Elongation (%)
1	502	401.5	109.13	48.4
2	463	370	132.29	57.5
3	548	438.5	140.51	49
4	543	434.5	126.28	47.8
5	576	460	104.73	63.6
6	482.5	386	98.47	45.3
7	489	391.5	94.95	47.4
8	555.7	444.5	115.77	46
9	508	406	112.89	59
10	562	449.5	98.60	54.1
Mean/S.D	**522.92/±38.71**	**418.2/±30.90**	**113.36/±15.41**	**51.81/±6.32**

INFERENCE:

For the laser treated Ni-Cr samples (Test group I), the basic mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation were found to be 522.92 Mpa, 418.2 Mpa, 113.36 Gpa and 51.81% respectively.

Table 6: Basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Co-Cr samples after laser peening (Test group II)

Sample No	Ultimate tensile strength (Mpa)	Yield strength 0.2% (Mpa)	Elastic modulus (Gpa)	Elongation (%)
1	629	503.2	149.76	18.1
2	723	578.4	160.67	25.1
3	663	530.4	148.99	18.2
4	515	412	122.62	26.6
5	667	533.6	138.96	23
6	619	495.2	171.94	19.8
7	698	558.4	155.11	22.3
8	590	472	122.92	20
9	564	451	161.14	23.4
10	582	465.6	157.30	21.8
Mean/S.D	**625/±64.19**	**499.98/±51.37**	**148.94/±16.30**	**21.83/±2.82**

INFERENCE:

For the laser treated Co-Cr samples (Test group II), the basic mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation were found to be 625 Mpa, 499.98 Mpa, 148.94 Gpa and 21.83 % respectively.

Table 7: Basic values and mean values of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of CP-Ti samples after laser peening (Test group III)

Sample No	Ultimate tensile strength (Mpa)	Yield strength 0.2% (Mpa)	Elastic modulus (Gpa)	Elongation (%)
1	730	584	132.73	24.2
2	742	593.5	151.43	19.3
3	728	583	138.67	24.2
4	720.2	576	156.57	19.8
5	688.4	550.5	149.65	21
6	670.5	536.5	149	23
7	746	597	134.41	26
8	690.5	552.5	143.85	27.2
9	715	572	140.2	26
10	722.2	577.5	153.66	21.6
Mean/S.D	**715.26/24.60**	**572.25/19.72**	**145.01/8.26**	**23.23/2.74**

INFERENCE:

For the laser treated CP-Ti samples (Test group III), the basic mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation were found to be 715.26 Mpa, 572.25 Mpa, 145.01 Gpa and 23.23 % respectively.

Table 8: Comparison of Surface Hardness of Ni-Cr, Co-Cr and CP-Ti before (Control groups I, II & III) and after laser peening (Test groups I, II & III)

Groups	Surface Hardness (VHN)		
	Ni-Cr	**Co-Cr**	**CP-Ti**
Untreated (Control groups)	295.3	394	205.2
After laser peening (Test groups)	437	754.3	689

INFERENCE:

The surface hardness of Ni-Cr, Co-Cr and CP-Ti increased substantially after laser peening. After laser treatment, the Co-Cr samples had the highest surface hardness followed by CP-Ti and Ni-Cr.

Table 9: Comparison of means of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Ni-Cr samples before (Control group I) and after laser peening (Test group I)

One sample T-test

Ni-Cr Samples	**Ultimate Tensile strength (Mpa)**	**Yield strength 0.2% (Mpa)**	**Elastic modulus (Gpa)**	**Elongation (%)**
Control group I	545.20	435.88	131.78	23.6
Test group I	522.92	418.20	113.36	51.81
P-value	0.102	0.104	0.004*	0.000*

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparing the mechanical properties of Ni-Cr samples before and after laser peening, the ultimate tensile strength and yield strength reduced marginally after laser peening but they were not significantly different from the values of untreated samples. The modulus of elasticity reduced after laser peening and it showed statistically significant difference from the untreated samples. Percentage of elongation increased after laser peening and it showed statistically significant difference from the untreated samples.

Table 10: Comparison of means of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of Co-Cr samples before (Control group II) and after laser peening (Test group II)

One sample T-test

Co-Cr Samples	**Ultimate Tensile strength (Mpa)**	**Yield strength 0.2% (Mpa)**	**Elastic modulus (Gpa)**	**Elongation (%)**
Control group II	671.04	536.90	148.85	18.14
Test group II	625	499.98	148.94	21.83
P-value	0.050*	0.049*	0.986	0.003*

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparing the mechanical properties of Co-Cr samples before and after laser peening, the ultimate tensile strength and yield strength reduced after laser peening and it showed statistically significant difference from the untreated samples. The modulus of elasticity of laser treated samples increased marginally than the untreated samples but they did not show statistically significant difference. Percentage of elongation increased after laser peening and it showed statistically significant difference from the untreated samples.

Table 11: Comparison of means of Ultimate tensile strength, Yield strength, Modulus of elasticity and Percentage of elongation of CP-Ti samples before (Control group III) and after laser peening (Test group III)

One sample T-test

CP-Ti Samples	Ultimate Tensile strength (Mpa)	Yield strength 0.2% (Mpa)	Elastic modulus (Gpa)	Elongation (%)
Control group III	375.04	300.08	100.35	23.98
Test group III	715.26	572.25	145.01	23.23
P-value	0.000*	0.000*	0.000*	0.410

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparing the mechanical properties of CP-Ti samples before and after laser peening, the ultimate tensile strength, yield strength and modulus of elasticity increased after laser peening and they showed statistically significantly differences from the values of untreated samples. Percentage of elongation reduced marginally after laser peening and it did not show any significant difference.

Table 12: Comparison of means of Ultimate tensile strength of Ni-Cr, Co-Cr and CP-Ti samples before laser peening (Control groups I, II & III)

One way Analysis of variance (ANOVA)

Control groups	**Mean (Mpa)**	**S.D**	**P-value**
Ni-Cr - Group I	545.20	15.91	0.000*
Co-Cr - Group II	671.04	28.56	
CP-Ti – Group III	375.04	16.37	

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparison, the mean ultimate tensile strength of untreated Co-Cr samples was the highest (671.04) followed by Ni-Cr (545.20 Mpa) and CP-Ti (375.04 Mpa) samples. They exhibited statistically significant differences at 5 % level.

Post-hoc Tukey HSD analysis

Control groups	**P-value**
Group I - Group II	0.000*
Group II - Group III	0.000*
Group III - Group I	0.000*

Note: * The mean difference is significant at the 0.05 level.

Inference:

Statistically significant differences exist between all pairs. (Group I & II), (Group II & III) and (Group III & I)

Table 13: Comparison of means of Yield strength of Ni-Cr, Co-Cr and CP-Ti samples before laser peening (Control groups I, II & III)

One way Analysis of variance (ANOVA)

Control groups	**Mean 0.2% (Mpa)**	**S.D**	**P-value**
Ni-Cr - Group I	457.68	46.55	0.000*
Co-Cr - Group II	536.90	22.90	
CP-Ti – Group III	300.08	13.17	

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparison, the mean yield strength of untreated Co-Cr samples was the highest (536.90 Mpa) followed by Ni-Cr **(**457.68 Mpa) and CP-Ti (300.08 Mpa) samples. They exhibited statistically significant differences at 5 % level.

Post-hoc Tukey HSD analysis

Control groups	**P-value**
Group I - Group II	0.004*
Group II - Group III	0.000*
Group III - Group I	0.000*

Note: * The mean difference is significant at the 0.05 level.

Inference:

Statistically significant differences exist between all pairs (Group I & II), (Group II & III) and (Group III & I).

Table 14: Comparison of means of Modulus of elasticity of Ni-Cr, Co-Cr and CP-Ti samples before laser peening (Control groups I, II & III)

One way Analysis of variance (ANOVA)

Control groups	**Mean (Gpa)**	**S.D**	**P-value**
Ni-Cr - Group I	131.78	10.09	0.000*
Co-Cr - Group II	148.85	12.94	
CP-Ti – Group III	100.34	3.43	

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparison, the mean modulus of elasticity of untreated Co-Cr samples was the highest (148.85 Gpa) followed by Ni-Cr (131.78 Gpa) and CP-Ti (100.34 Gpa) samples. They exhibited statistically significant differences at 5 % level.

Post-hoc Tukey HSD analysis

Control groups	**P-value**
Group I - Group II	0.040*
Group II - Group III	0.000*
Group III - Group I	0.001*

Note: * The mean difference is significant at the 0.05 level.

Inference:

Statistically significant differences exist between all pairs (Group I & II), (Group II & III) and (Group III & I).

Table 15: Comparison of means of Percentage of elongation of Ni-Cr, Co-Cr and CP-Ti samples before laser peening (Control groups I, II & III)

One way Analysis of variance (ANOVA)

Control groups	**Mean (%)**	**S.D**	**P-value**
Ni-Cr - Group I	23.60	3.57	0.109
Co-Cr - Group II	18.14	3.52	
CP-Ti – Group III	23.98	5.88	

Note: * The mean difference is significant at the 0.05 level.

Inference:

The mean percentage of elongation of untreated Co-Cr samples was the highest (23.98 %) followed by Ni-Cr (23.60 %) and CP-Ti (18.14 %) samples. No statistically significant differences were observed between the three groups.

Post-hoc Tukey HSD analysis

Control groups	**P-value**
Group I - Group II	0.172
Group II - Group III	0. 139
Group III - Group I	0.990

Note: * The mean difference is significant at the 0.05 level.

Inference:

No statistically significant difference exists between all pairs (Group I & II), (Group I & III) and (Group II & III).

Table 16: Comparison of means of Ultimate tensile strength of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)

One way Analysis of variance (ANOVA)

Test groups	Mean (Mpa)	S.D	P-value
Ni-Cr - Group I	522.92	38.71	0.000*
Co-Cr - Group II	625.00	64.19	
CP-Ti – Group III	715.26	24.60	

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparison, the mean ultimate tensile strength of laser treated samples was highest for the CP-Ti samples (715.26 Mpa) followed by Co-Cr (625 Mpa) and Ni-Cr (522.92 Mpa) samples. They exhibited statistically significant differences at 5 % level.

Post-hoc Tukey HSD analysis

Control groups	P-value
Group I - Group II	0.000*
Group II - Group III	0.000*
Group III - Group I	0.000*

Note: * The mean difference is significant at the 0.05 level.

Inference:

Statistically significant differences exist between all pairs (Group I & II), (Group II & III) and (Group III & I).

Table 17: Comparison of means of Yield strength of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)

One way Analysis of variance (ANOVA)

Test groups	**Mean 0.2% (Mpa)**	**S.D**	**P-value**
Ni-Cr - Group I	418.20	30.90	0.000*
Co-Cr - Group II	499.98	51.37	
CP-Ti – Group III	572.25	19.72	

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparison, the mean yield strength of laser treated samples was highest for the CP-Ti samples (572.25 Mpa) followed by Co-Cr (499.98 Mpa) and Ni-Cr (418.20 Mpa) samples. They exhibited statistically significant differences at 5 % level.

Post-hoc Tukey HSD analysis

Control groups	**P-value**
Group I - Group II	0.000*
Group II - Group III	0.000*
Group III - Group I	0.000*

Note: * The mean difference is significant at the 0.05 level.

Inference:

Statistically significant differences exist between all pairs (Group I & II), (Group II & III) and (Group III & I)

Table 18: Comparison of means of Modulus of elasticity of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)

One way Analysis of variance (ANOVA)

Test groups	**Mean (Gpa)**	**S.D**	**P-value**
Ni-Cr - Group I	113.36	15.41	0.000*
Co-Cr - Group II	148.94	16.30	
CP-Ti – Group III	145.01	8.26	

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparison, the mean modulus of elasticity of laser treated samples was highest for the Co-Cr samples (148.94 Gpa) followed by CP-Ti **(**145.01 Gpa) and Ni-Cr (113.36 Gpa) samples. They exhibited statistically significant differences at 5 % level.

Post-hoc Tukey HSD analysis

Control groups	**P-value**
Group I - Group II	0.000*
Group II - Group III	0.802
Group III - Group I	0.000*

Note: * The mean difference is significant at the 0.05 level.

Inference:

Statistically significant differences exist between Groups (I & II) and (III & I).No statistical significant difference between groups (II & III).

Table 19: Comparison of means of Percentage of elongation of Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III)

One way Analysis of variance (ANOVA)

Test groups	**Mean (%)**	**S.D**	**P-value**
Ni-Cr - Group I	51.81	6.32	0.000*
Co-Cr - Group II	21.83	2.82	
CP-Ti – Group III	23.23	2.74	

Note: * The mean difference is significant at the 0.05 level.

Inference:

On comparison, the mean percentage of elongation of laser treated samples was highest for the Ni-Cr samples (51.81 %) followed by CP-Ti **(**23.23 %) and Co-Cr (21.83 %) samples. They exhibited statistically significant differences at 5 % level.

Post-hoc Tukey HSD analysis

Control groups	**P-value**
Group I - Group II	0.000*
Group II - Group III	0.749
Group III - Group I	0.000*

Note: * The mean difference is significant at the 0.05 level.

Inference:

Statistically significant differences exist between Groups (I & II) and (III & I). No statistical significant difference between groups (II & III).

DISCUSSION

Prosthodontic procedures involve not only application of non-metallic materials but also metals and alloys for use in various applications.[2] Alloys have been considered as paramount importance in the field of fixed and removable prosthodontics. This is because, alloys have been proven to have excellent mechanical properties which are the most essential requirement for the successful service of these prosthesis[55] and they also have been proved to have superior accuracy of fit.[36]

Although all-ceramic restorations have received much promotion in recent years due to their excellent esthetics, they currently are not a viable replacement for the metal-ceramic restoration. The vast majority of tooth coloured restorations are still metal-ceramic; these restorations have proven, long-term clinical records that are not available for any all-ceramic system. All-ceramic systems require the removal of significantly more tooth structure and are susceptible to fracture, especially in posterior teeth or in fixed partial denture applications. If properly constructed by a qualified laboratory technologist, the traditional metal-ceramic restoration can yield excellent esthetic results.[54]

Dental casting alloys are used for the fabrication of fixed and removable prosthesis by casting procedures. Even though noble and high-noble alloys were considered for prosthodontic use till a few decades ago, base metal alloys have evolved as an alternative due to various reasons such as: lower cost of the alloy, superior mechanical properties such as ultimate tensile strength, yield strength, modulus of elasticity, percentage elongation, hardness, high melting range compatible with ceramic application, etc.[36,45]

The primary physical properties of base-metal alloys include a lower density than gold alloys, a particularly useful property when fabricating bulky prostheses. Also, their elastic moduli are nearly twice that of gold alloys, providing fixed and removable partial dentures with the advantage of maintaining rigidity with less bulk.[2,15,17,54,55]

Although base metal alloys, such as Nickel-chromium (Ni-Cr) and Cobalt-chromium (Co-Cr) have been widely used in the fabrication of metal ceramic crowns and fixed partial dentures, there are concerns about their biological safety following reports of nickel and cobalt sensitivity in patients.[22,42,43,53]

In recent years, titanium has become a material of great interest in prosthodontics. Commercially pure titanium (CP-Ti) and its alloys have become an alternative to gold and base metal alloys[7,9,18,25] because of their excellent biocompatibility,[4,9,33] good corrosion resistance[4,9,11] and low density.[19] Its high strength-to-weight ratio and high mechanical resistance permit the design of more functional and comfortable prosthesis.[42]

In spite of the many desirable characteristics of titanium, mechanical properties of CP-Ti are inferior when compared to Ni-Cr and Co-Cr alloys.[23,26] Published literature comparing the mechanical properties of CP-Ti and its alloys with Ni-Cr and Co-Cr alloys are available.[7,10,11,18,31,34,38,39,41,45,48,49,52] Values of important mechanical properties such as ultimate tensile strength, yield strength, modulus of elasticity and hardness of CP-Ti are very much lesser when compared to Ni-Cr and Co-Cr.[20,37,39,40,43,45,58] The most widely used titanium alloy is Ti-6Al-4V. Although this alloy has greater strength than CP-Ti and similar mechanical properties like Ni-Cr and Co-Cr alloys,[68] it is not as attractive from a biocompatibility point of view because of some concerns about health hazards from the slow release of aluminium and vanadium.[26,33] Long span fixed prosthesis and removable partial denture frameworks, of which alloys are an integral part, may often require superior mechanical properties.[8,20,26,30,32,33] The mechanical properties such as microhardness, ultimate tensile strength, yield strength, modulus of elasticity and percentage elongation are important as they are directly linked to long term clinical performance.[50]

There are various methods used in past for improving the mechanical properties of metals such as compositional alterations[54] and heat treatment of alloys.[12,60] Recently an innovative laser surface treatment process called laser peening has been employed for improving mechanical properties of CP-Ti.[43,57]

In this study, comparative evaluation of the mechanical properties of base metal alloys and commercially pure titanium with effect of laser surface treatment was done. It was done in an attempt to increase the mechanical properties of CP-Ti. Ni-Cr and Co-Cr alloys were also included in the study for comparison.

The cast samples for the study were standardized as per ISO specifications, so as to have all the specimens in exactly the same dimensions, by using a metal die. A total of (n=17) Ni-Cr samples (Group I), (n=17) Co-Cr samples (Group II) and (n=17) CP-Ti samples (Group III) were obtained after casting. Six (n=6) samples from each group served as Control group without subjecting to laser peening while eleven (n=11) samples from each group were individually subjected to laser peening (Test group).

Ni-Cr, Co-Cr and CP-Ti samples were tested for important mechanical properties like ultimate tensile strength, yield strength, modulus of elasticity and percentage elongation before (Control groups) and after laser peening (Test groups). One representative sample from Ni-Cr, Co-Cr and CP-Ti each from control and test group was used to evaluate the Vickers microhardness. In order to evaluate hardness separate sample was used so that the influence of tensile force will not affect the hardness of alloy.

Among the various methods of improving mechanical properties, laser peening was considered in this study as they are more effective.[43,57] The laser drives a high-amplitude shock wave into a material surface using a high energy pulsed laser. When laser is applied to cast titanium metal frameworks, it is expected that the titanium framework will have high mechanical strength to withstand mastication stress. Laser parameters were set for this study in accordance with parameters used in previous studies.[43,57] Laser peening was performed using a dental Nd:YAG laser welding machine (Lee laser, Q-switched, U.S.A) using the following parameters for all the three groups: spot diameter of 1.2 mm, pulse duration of 10 ms, frequency of 1.1Khz and fluence value of 450 J/Cm^2.

Using the Tensometer, the mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage elongation of untreated (Control groups) and laser treated (Test groups) Ni-Cr, Co-Cr and CP-Ti samples were obtained. Using the Vickers microhardness tester, measurements of hardness from surface to a depth of 450 µm of one representative sample from both control and test groups of Ni-Cr, Co-Cr and CP-Ti were obtained.

The hardness of untreated (Control group) Ni-Cr, Co-Cr and CP-Ti were found to be 295.3 VHN, 394 VHN and 205.2 VHN in the surface respectively and they had increased significantly to 437 VHN, 754.3 VHN and 689 VHN respectively upon laser peening (Test groups). Microscopic examination revealed marginal burnout of metal matrix for Ni-Cr sample followed by change in grain size in the heat affected zone. Marginal change of grain structure from austenitic to martensitic phase was observed in Co-Cr sample.

Significant increase of hardness at a depth of 450 μm for CP-Ti was observed after laser peening. This could be contributed to the change of phase structure from alpha-phase to beta-phase in the CP-Ti as seen in the metallurgical microscopic image. Three zones were observed in metallurgical microscopic image of laser treated CP-Ti: laser melted zone (LMZ), heat affected zone (HAZ) and raw material (RM). The RM microstructure of as-cast CP-Ti was mainly composed of alpha grains while the LMZ was characterized by large size columnar beta grains. Also, because of low thermal conductivity of CP-Ti penetration of laser increased much efficiently in the surface of laser even at a greater depth in comparison to Ni-Cr and Co-Cr samples.[35,56]

The hardness value of Ni-Cr, Co-Cr and CP-Ti increased significantly and they met the minimum requirement of 150 VHN for FPD alloys.[54,55] The hardness values achieved for untreated samples in this study are comparable to those reported in literature.[6,11,18,31,34,38,41,46,47,48,49,58] The hardness values for laser treated CP-Ti samples were almost similar to the values reported by Watanabe et al.[43,57]

The mean values of ultimate tensile strength of untreated (Control group) Ni-Cr, Co-Cr and CP-Ti were found to be 545.2 Mpa, 671.04 Mpa and 375.04 Mpa respectively. They were in accordance with the previously reported studies.[6,7,10,18,31,34,39,41,43,45,46,57,58] After laser peening mean values of Ni-Cr and Co-Cr were found to be 522.92 Mpa and 625 Mpa which was slightly lower than the control group. But for CP-Ti the mean value was found to be 715.26 Mpa which was significantly higher than control group and were almost similar to the values reported by Watanabe et al.[43,57]

The mean values of yield strength of untreated (Control group) Ni-Cr, Co-Cr and CP-Ti were found to be 435.88 Mpa, 536.9 Mpa and 300.08 Mpa respectively. They were in accordance with the previously reported studies.[7,10,18,31,35,39,45,46,58] The acceptable yield strength threshold value according to ISO standards 9693[27] and 6871[28,29] for alloys used for the metal-ceramic FPDs and construction of RPDs is 250 Mpa and 500 Mpa, respectively. Although values of untreated (Control group) Ni-Cr ,Co-Cr and CP-Ti met the minimum requirement of metal-ceramic FPD purpose, the values of CP-Ti were inferior when compared to Ni-Cr and Co-Cr and it does not meet the minimum acceptable values for yield strength when used for RPDs. It was also likely to fail if used for long-span FPDs. After laser peening mean values of Ni-Cr and Co-Cr were found to be 418.2 Mpa and 499.98 Mpa which were slightly reduced but within the limits of ISO standards. But for CP-Ti the mean value was found to be 572.25 Mpa which was significantly higher to the level that it can be conveniently used for construction of RPD, meeting the requirements of ISO standards.

The mean values of modulus of elasticity of untreated (Control group) Ni-Cr, Co-Cr and CP-Ti were found to be 131.78 Gpa, 148.85 Gpa and 100.35 Gpa respectively. They were in accordance with the previously reported studies.[11,18,31,34,43,45,46,57,58] After laser peening mean values of Ni-Cr, Co-Cr and CP-Ti were found to be 113.36 Gpa, 148.94 Gpa and 145.01 Gpa respectively. After laser peening, mean values of Ni-Cr reduced significantly than control group. The mean values for Co-Cr marginally increased whereas the values for CP-Ti increased significantly and almost comparable to the modulus of Co-Cr alloys thus making it favourable for long-span FPDs and for construction of cast partial RPDs.

The mean values of percentage elongation of untreated (Control group) Ni-Cr, Co-Cr and CP-Ti were found to be 23.6 %, 18.14 % and 23.98 % respectively. They were in accordance with the previously reported studies.[6,7,18,34,39,43,45,46,57,58] After laser peening, mean value of Ni-Cr was found to be 51.81 % which was significantly higher than control group. The mean value of Co-Cr was found to be 21.83 % which was also significantly higher than control group and the value for CP-Ti was found to be 23.23% which marginally reduced when compared to control group.

The influence of laser peening on Ni-Cr and Co-Cr alloys are lacking in literature. This study shows that the effect of laser peening on Ni-Cr and Co-Cr was minimal and mechanical properties were not enhanced with the exception of rise in percentage elongation for Ni-Cr alloy and modulus of elasticity for Co-Cr. The possible explanation for this is may be the absence of microstructural phase change from austenitic to martensitic transformation with this laser setting used for laser peening. This could be the reason which could be attributed for marginal reduction in the properties of Ni-Cr and Co-Cr, while CP-Ti showed enhanced values after laser peening.

The current study indicate that all the essential mechanical properties like hardness, ultimate tensile strength, yield strength, modulus of elasticity and percentage elongation for CP-Ti are increased by the effect of laser peening and these mechanical properties meet the mechanical requirements for FPDs and cast partial RPDs making them suitable for use in dentistry. Considering its biocompatibility CP-Ti when laser treated might be an ideal material of choice for prosthodontic restorations. It will also alleviate the fear of cytotoxic effects of vanadium present in commonly used Ti-6Al-4V alloys.

The drawbacks of this present study were that it was done on samples based on ISO requirement. Clinical performance can be accessed by laser treating cast partial removable partial dentures or fixed partial dentures to simulate a clinical situation. Also only limited mechanical properties have been evaluated in this study. Other mechanical properties such as fatigue strength, torsional strength, impact strength, bending strength, biological behaviour and corrosive properties need to be evaluated. Properties such as bonding to ceramic after laser treatment and studies simulating wear of opposing dentition needs to be evaluated in further studies.

CONCLUSION

The following conclusions were drawn within the limitations of this in vitro study, which comparatively evaluated the mechanical properties of base metal alloys and commercially pure titanium with effect of laser surface treatment:

1. The value of surface hardness for untreated Ni-Cr sample (Control group I) was found to be 295.3 VHN and for laser treated Ni-Cr sample (Test group I) was found to be 437 VHN.

2. The value of surface hardness for untreated Co-Cr sample (Control group II) was found to be 394 VHN and for laser treated Co-Cr sample (Test group II) was found to be 754.3 VHN.

3. The value of surface hardness for untreated CP-Ti sample (Control group III) was found to be 205.2 VHN and for laser treated CP-Ti sample (Test group III) was found to be 689 VHN.

4. The mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of Ni-Cr samples (Control group I) were 545.2 Mpa, 435.88 Mpa, 131.78 Gpa and 23.6 % respectively.

5. The mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of Co-Cr samples (Control

group II) were 671.04 Mpa,536.9 Mpa,148.85 Gpa and 18.14 % respectively.

6. The mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of CP-Ti samples (Control group III) were 375.04 Mpa,300.08 Mpa,100.35 Gpa and 23.98 % respectively.

7. The mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of Ni-Cr samples after laser peening (Test group I) were 522.92 Mpa, 418.2 Mpa, 113.36 Gpa and 51.81 % respectively.

8. The mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of Co-Cr samples after laser peening (Test group II) were 625 Mpa, 499.98 Mpa, 148.94 Gpa and 21.83 % respectively.

9. The mean values of ultimate tensile strength, yield strength, modulus of elasticity and percentage of elongation of CP-Ti samples after laser peening (Test group III) were 715.26 Mpa, 572.25 Mpa, 145.01 Gpa and 23.23 % respectively.

10. On comparison of surface hardness of Ni-Cr, Co-Cr and CP-Ti samples before (Control groups I, II & III) and after laser peening (Test groups I, II & III), the surface hardness has increased for Ni-Cr, Co-Cr and

CP-Ti samples after laser peening substantially. Co-Cr had the maximum surface hardness (754 VHN) followed by CP-Ti (689 VHN) and Ni-Cr (437 VHN) after laser peening.

11. On comparison of the means of ultimate tensile strength of Ni-Cr samples before (Control group I) and after laser peening (Test group I), the mean value of ultimate tensile strength for untreated and laser treated samples were 545.20 Mpa and 522.92 Mpa respectively. Laser peening has reduced the ultimate tensile strength of Ni-Cr samples but it does not have any statistical significance.

12. On comparison of the means of yield strength of Ni-Cr samples before (Control group I) and after laser peening (Test group I), the mean value of yield strength for untreated and laser treated samples were 435.88 Mpa and 418.20 Mpa respectively. Laser peening has reduced the yield strength of Ni-Cr samples but it does not have any statistical significance.

13. On comparison of the means of modulus of elasticity of Ni-Cr samples before (Control group I) and after laser peening (Test group I), the mean value of modulus of elasticity for untreated and laser treated samples were 131.78 Gpa and 113.36 Gpa respectively. Laser peening has reduced the modulus of elasticity of Ni-Cr samples and they showed statistically significant differences between them.

14. On comparison of the means of percentage of elongation of Ni-Cr samples before (Control group I) and after laser peening (Test group I), the mean value of percentage of elongation for untreated and laser treated samples were 23.6 % and 51.81 % respectively. Laser peening has increased the percentage of elongation of Ni-Cr samples and they showed statistically significant differences between them.

15. On comparison of the means of ultimate tensile strength of Co-Cr samples before (Control group II) and after laser peening (Test group II), the mean value of ultimate tensile strength for untreated and laser treated samples were 671.04 Mpa and 625 Mpa respectively. Laser peening has reduced the ultimate tensile strength of Co-Cr samples and they showed statistically significance differences between them.

16. On comparison of the means of yield strength of Co-Cr samples before (Control group II) and after laser peening (Test group II), the mean value of yield strength for untreated and laser treated samples were 536.90 Mpa and 499.98 Mpa respectively. Laser peening has reduced the yield strength of Co-Cr samples and they showed statistically significance differences present between them.

17. On comparison of the means of modulus of elasticity of Co-Cr samples before (Control group II) and after laser peening (Test group II), the mean value of modulus of elasticity for untreated and laser treated

samples were 148.85 Gpa and 148.94 Gpa respectively. Laser peening has increased the modulus of elasticity of Co-Cr samples marginally but it does not have any statistically significant differences between them.

18. On comparison of the means of percentage of elongation of Co-Cr samples before (Control group II) and after laser peening (Test group II), the mean value of percentage of elongation for untreated and laser treated samples were 18.14 % and 21.83 % respectively. Laser peening has increased the percentage of elongation of Co-Cr samples and they showed statistically significant differences present between them.

19. On comparison of the means of ultimate tensile strength of CP-Ti samples before (Control group III) and after laser peening (Test group III), the mean value of ultimate tensile strength for untreated and laser treated samples were 375.04 Mpa and 715.26 Mpa respectively. Laser peening has increased the ultimate tensile strength of CP-Ti samples and they showed statistically significant differences present between them.

20. On comparison of the means of yield strength of CP-Ti samples before (Control group III) and after laser peening (Test group III), the mean value of yield strength for untreated and laser treated samples were 300.08 Mpa and 572.25 Mpa respectively. Laser peening has increased

the yield strength of CP-Ti samples and they showed statistically significant differences present between them.

21. On comparison of the means of modulus of elasticity of CP-Ti samples before (Control group III) and after laser peening (Test group III), the mean value of modulus of elasticity for untreated and laser treated samples were 100.35 Gpa and 145.01 Gpa respectively. Laser peening has increased the modulus of elasticity of CP-Ti samples and they showed statistically significant differences present between them.
22. On comparison of the means of percentage of elongation of CP-Ti samples before (Control group III) and after laser peening (Test group III), the mean value of percentage of elongation for untreated and laser treated samples were 23.98 % and 23.23 % respectively. Laser peening has marginally reduced the percentage of elongation of CP-Ti samples but it does not have any statistical significance.
23. On comparison of mean values of ultimate tensile strength between untreated Ni-Cr, Co-Cr and CP-Ti samples (Control groups I, II & III), mean value for Co-Cr samples (671.04 Mpa) was the highest followed by Ni-Cr samples (545.20 Mpa) and CP-Ti samples (375.04 Mpa). Statistically significant difference exists between groups I &II, groups II & III and groups III & I with P-value 0.000.
24. On comparison of mean values of yield strength between untreated Ni-Cr, Co-Cr and CP-Ti samples (Control groups I, II &III),mean

value for Co-Cr samples (536.90 Mpa) was the highest followed by Ni-Cr samples (457.68 Mpa) and CP-Ti samples (300.08 Mpa). Statistically significant difference exists between groups I &II with P-value 0.004, groups II & III and groups III & I with P-value 0.000.

25. On comparison of mean values of modulus of elasticity between untreated Ni-Cr, Co-Cr and CP-Ti samples (Control groups I, II & III), mean value for Co-Cr samples (148.85 Gpa) was the highest followed by Ni-Cr samples (131.78 Gpa) and CP-Ti samples (100.34 Gpa). Statistically significant difference exists between groups II & III with P-value 0.000, between groups III & I with P-value 0.001 and groups I & II with P-value 0.040.

26. On comparison of mean values of percentage of elongation between untreated Ni-Cr, Co-Cr and CP-Ti samples (Control groups I,II & III), mean value for CP-Ti samples (23.98 %) was the highest followed by Ni-Cr samples (23.60 %) and Co-Cr samples (18.14 %). No statistically significant difference exists between groups I & II, groups II & III and groups III & I were observed.

27. On comparison of mean values of ultimate tensile strength between Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I,II&III), mean value for CP-Ti samples (715.26 Mpa) was the highest followed by Co-Cr samples (625 Mpa) and Ni-Cr samples

(522.92 Mpa). Statistically significant difference exists between groups I & II, groups II & III and groups III & I with P-value 0.000.

28. On comparison of mean values of yield strength between Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I,II & III), mean value for CP-Ti samples (572.25 Mpa) was the highest followed by Co-Cr samples (499.98 Mpa) and Ni-Cr samples (418.20 Mpa). Statistically significant difference exists between groups I &II, groups II & III and groups III & I with P-value 0.000.

29. On comparison of mean values of modulus of elasticity between Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III), mean value for Co-Cr samples (148.94 Gpa) was the highest followed by CP-Ti samples (145.01 Gpa) and Ni-Cr samples (113.36 Gpa). Statistically significant difference exists between groups I & II and groups III & I with P-value 0.000, but groups II & III were not statistically significant.

30. On comparison of mean values of percentage of elongation between Ni-Cr, Co-Cr and CP-Ti samples after laser peening (Test groups I, II & III), mean value for Ni-Cr samples (51.81 %) was the highest followed by CP-Ti samples (23.23 %) and Co-Cr samples (21.83 %). Statistically significant difference exists between groups I & II and groups III & I with P-value 0.000, but groups II & III were not statistically significant.

SUMMARY

The present in vitro study was conducted to comparatively evaluate the mechanical properties of base metal alloys and commercially pure titanium with effect of laser surface treatment.

A total of 51 dumbbell shaped cast samples for this study were fabricated with Ni-Cr (n=17), Co-Cr (n=17) and CP-Ti (n=17) as per ISO specifications and grouped as Group I for Ni-Cr, Group II for Co-Cr and Group III for CP-Ti. 6 cast samples from each group served as Control group without subjecting to laser peening while 11 cast samples from each group was subjected to laser peening (Test group).

Cross section of 1 untreated Control group cast sample of Ni-Cr, Co-Cr and CP-Ti each (Control groups I, II and III) and cross section of 1 Test group cast sample of Ni-Cr, Co-Cr and CP-Ti each after laser peening (Test groups I, II and III) were subjected to microscopic examination following which microhardness was evaluated from the cast surface to 450μm in depth using micro Vickers hardness tester.

Tensile testing of 5 control group cast samples and 10 test group cast samples each for Ni-Cr, Co-Cr and CP-Ti groups were conducted using tensometer machine at a cross head speed of 0.5mm/min to determine the Ultimate Tensile Strength (Mpa),Yield Strength (Mpa), Modulus of Elasticity (Gpa) and Percentage Elongation (%). The results obtained were tabulated and statistically analysed.

Microscopic examination revealed marginal burnout of metal matrix and change in grain size in the heat affected zone for Ni-Cr sample, marginal austenitic to martensitic phase change with larger grain size occurred for Co-Cr sample while alpha-phase to beta-phase transformation occurred for CP-Ti sample. Upon laser surface treatment surface hardness increased for Ni-Cr, Co-Cr and CP-Ti samples.

Ultimate Tensile Strength and Yield Strength of CP-Ti increased significantly upon laser peening whereas these values reduced for Ni-Cr and Co-Cr samples. Modulus of elasticity of CP-Ti increased significantly upon laser peening whereas it increased marginally for Co-Cr and reduced for Ni-Cr. Percentage of Elongation increased significantly for Ni-Cr and Co-Cr while it marginally reduced for CP-Ti samples.

Effect of laser surface treatment resulted in significant improvement of mechanical properties for CP-Ti whereas for Ni-Cr and Co-Cr samples it has not shown much improvement. Laser peening for CP-Ti resulted in improvement of mechanical properties to meet the requirements of ISO recommendations for the fabrication of prosthodontic restorations. Henceforth, laser treated CP-Ti can be considered a good alternative to noble and base metal alloys for prosthetic restorations.

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